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Brown, R.; Daley, C.

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Computer Simulation of Transverse Ship-Ice Collisions

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By

Robert Brown and Claude Daley
Faculty of Engineering and Applied Science
Memorial University of Newfoundland

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St. John's, NF, A1B 3X5
Canada

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1. INTRODUCTION

The East Coast of Canada has become one of the major offshore oil regions in the world. The unique aspect of the region is the presence of ice, both in the form of sea ice and icebergs. After a GBS structure at Hibernia, the Terra Nova oilfield is being developed with a ship-shape moored structure. The problem of transverse ship-ice collisions has become a significant concern.

The work described herein deals with the simulation of transverse collisions between a stationary ship and a spherical iceberg moving with constant initial velocity. The study makes many simplifying assumptions, and mainly serves to set the scope of the problem.

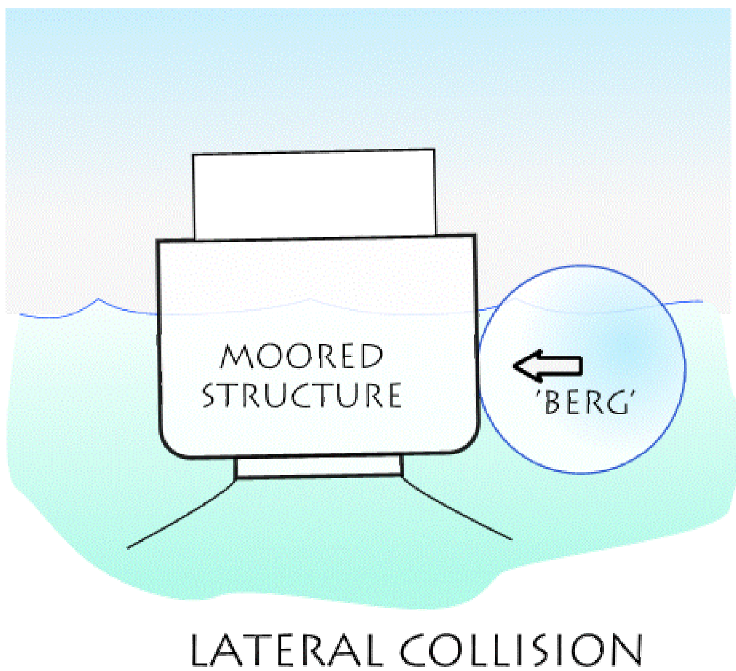


Figure 1. Lateral collision between ice and a moored ship-shaped offshore structure.

1.1. Ice Collision Mechanics

To understand the current problem, the general nature of ice-structure collision is outlined. This will place the current analysis in perspective. There are various ship-structure scenarios that have been studied. Four scenarios, with their key features are given in Table 1.

Table 1. Collision scenarios and key features.

Scenario	Features/Aspects
ramming	• ship moving forward • motions in vertical plane • ship comes to full stop
glancing	• ship moving forward • ship moves in 3D • ship does not stop
lateral collision	• ship stopped or turning • contact on side shell • motion 2D or 3D
general	• any structure /any ice • simultaneous collisions • hydrodynamics

For any of these scenarios the collision analysis rests on mechanical principles and can be seen as either a balance of forces or a balance of energies. From an energy point of view, the key components of the energy balance are shown in Figure 2. The energy is initially kinetic energy, and is converted (lost) in crushing, friction and wave making. The simplest models assume that only the kinetic energy and crushing need be considered. The most elaborate models will consider all aspects.

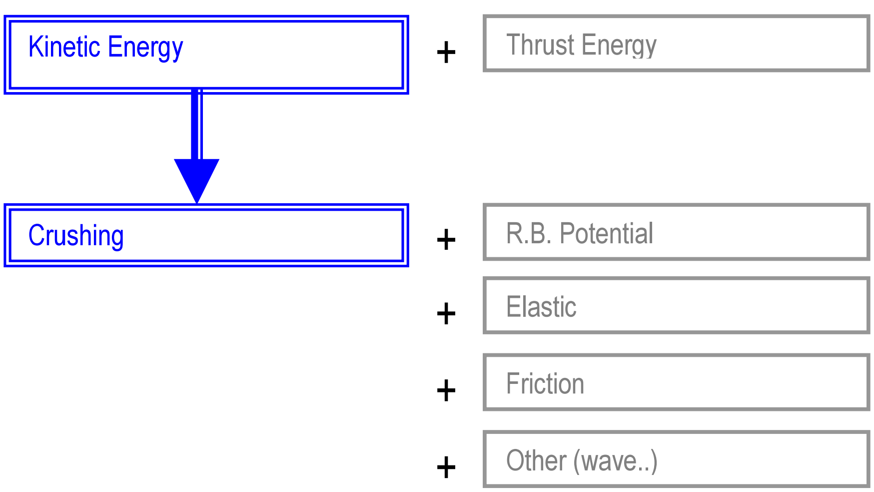


Figure 2. Components of energy in ship-ice collision

There are various methodologies that can be used to pose and solve the equations describing the collision. These include:

- analytical
  - **energy based solutions (e.g. Popov)**
  - time based Laplace solution (e.g. Riska)
- numerical
  - procedural software (e.g. VBasic)
  - equation solvers (e.g. Mathcad)
  - **simulation software (e.g. WorkingModel)**

In this work, we have investigated the collision using two approaches, a numerical simulation (based on Working model 2D) and an energy-based analytical solution.

1.2. Software

Simulations were conducted using the educational version (V4.01) of Working Model 2D software. This software package has been developed for use in simulating the mechanical behaviour of rigid bodies. It has a programmable component that allows the user to specify conditions and enter formulas based on these conditions. Also, objects modeled within the software have certain properties that can be modified to approximate the 'real world' case.

1.3. Simulation Matrix

A comprehensive matrix of simulation conditions was developed to provide a realistic cross-section of collision scenarios. All reasonable combinations of four ship displacements, and five ice displacements, along with three initial ice velocities and five pressure-area relationship exponents were made to produce a test matrix of 150 simulations. The matrix is given in Table 2.

Table 2. Simulation Matrix.

Ship Displ. (ktonne)	Ice Displ. (tonne)	Ice Velocity (m/s)	Area Exponent
10	50	0.5, 1.0, 2.0	0, -0.1, -0.3, -0.5, -0.7
10	100	0.5, 1.0, 2.0	0, -0.1, -0.3, -0.5, -0.7
20	100	0.5, 1.0, 2.0	0, -0.1, -0.3, -0.5, -0.7
20	1000	0.5, 1.0, 2.0	0, -0.1, -0.3, -0.5, -0.7
40	100	0.5, 1.0, 2.0	0, -0.1, -0.3, -0.5, -0.7
40	1000	0.5, 1.0, 2.0	0, -0.1, -0.3, -0.5, -0.7
40	5000	0.5, 1.0, 2.0	0, -0.1, -0.3, -0.5, -0.7
100	1000	0.5, 1.0, 2.0	0, -0.1, -0.3, -0.5, -0.7
100	5000	0.5, 1.0, 2.0	0, -0.1, -0.3, -0.5, -0.7
100	10000	0.5, 1.0, 2.0	0, -0.1, -0.3, -0.5, -0.7

2. DESCRIPTION OF THE MODEL

2.1. General Assumptions of the Model

Since Working Model 2D is not built for directly modeling hydrostatic scenarios as presented here, considerable thought was required to setup conditions that would allow for reasonably realistic simulations. In order to make objects float in the software environment a vertical force was applied to the centre of gravity of each object. Using the x-axis as the waterline, any vertical displacement of the ship or ice from this equilibrium position would cause it to oscillate up and down as if floating in water. The Working Model environment allows the user to change the value of air resistance. For this situation, the value could be considered a fluid damping force, however, it was set to zero for the current stage of modeling since a suitable value of fluid damping was not known. Since this external force did not exist, any perturbation from the equilibrium position would continue perpetually since energy was not lost due to damping.

One of the more challenging aspects of developing the model was related to the fact that Working Model 2D is only capable of modeling rigid body motion and interaction. Since the process of ship-ice collision is anything but rigid body interaction, it was required to 'trick' the software into simulating this aspect of the model. This was done by turning off the software option for *object collisions*. Thus, the computer did not automatically detect when the boundary of one object passed over the boundary of another. Next, points were attached to the surface of each body – one to the iceberg and two to the ship (see Figure 3) - and their locations monitored continuously. When the point on the iceberg surface passed beyond a line connecting the two points on the surface of the ship's hull, a force was calculated on each body at the point of collision. This force was based on the pressure-area relationship described in section 2.2.

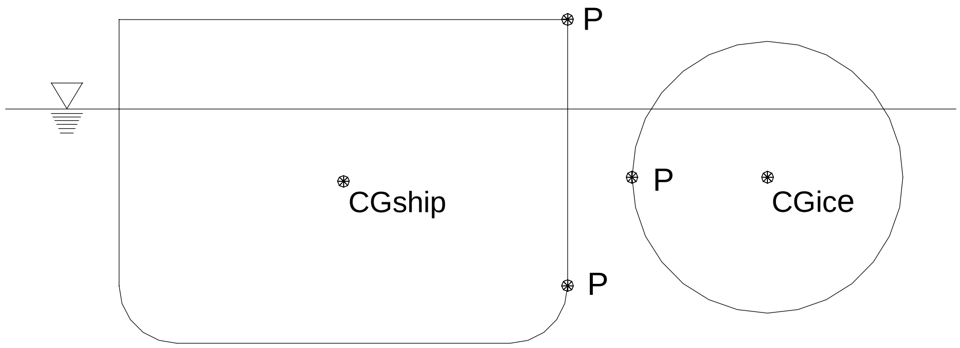


Figure 3. Points on ship and ice used to determine when impact occurred.

Since the body collision property of the ship and ice was turned off, no frictional forces were automatically present when collision occurred. To fix this, a frictional force was added to both the ship and iceberg. This force would become active as soon as the collision occurred, and acted normal to the collision force, causing the heeling moment to be slightly greater. The frictional coefficient assumed for the duration of simulations was 0.20 (IE. 20% of the collision force)

Finally, some other general assumptions include: the gravitational force acting on bodies was assumed to be equal to 9.807 m/s^2, water density is assumed to be that of salt water at 1025 kg/m^3, simulations were assumed to occur in calm, deep water, and integration/time stepping errors were assumed to be small within the software, since different values for error threshold and time step value were tested to find the best trade-off between simulation time and accuracy.

2.2. Ice Model

The ship-ice collision model is relatively simple to develop, assuming the collision is normal (force acts through the centre of gravity of the ship and ice) and the ship is considerably more massive than the ice (more than 10 times). Equating kinetic and crushing energy would allow for solution of the collision by hand.

Through the use of Working Model 2D software, all that is needed is to correctly model the ship/ice collision is an equation for force developed during the collision. Since the force is related to the pressure, we assume a pressure area relationship of the form:

$$\boldsymbol{P(A) = P_o A^{ex}} \qquad (1)$$

Where ^{ex} is the assumed area exponent, P(A) is the average pressure over the contact area A and P_o is the average pressure over 1 m^2. We also know that the force is given as:

$$\boldsymbol{F = PA \rightarrow F = P_o A^{ex} A \rightarrow F = P_o A^{(ex+1)}} \qquad (2)$$

In order to solve this equation in Working Model 2D we need to determine the value of the contact area for each time step. Since the value of contact area is not directly available within the software, it would be more useful to write the equation in terms of a variable that is directly available – the penetration. From Figure 4 we can see that the contact area of a sphere (iceberg) striking a flat plane (wall-sided ship hull) would be circular with radius r. The contact area would be:

$$\boldsymbol{A = \pi\ r^2} \qquad (3)$$

The value of r is found through basic geometry to be:

$$\boldsymbol{r = \sqrt{(2R\,p - p2)} \rightarrow r^2 = 2R\,p - p2} \qquad (4)$$

$$\boldsymbol{\therefore A = \pi\ (2R\,p - p^2)} \qquad (5)$$

(Note. for small values of p : $A \cong \pi(2R\,p)$)

Where $\boldsymbol{R}$ is the radius of the iceberg and $\boldsymbol{p}$ is the amount of penetration. Now that we know the contact area in terms of other directly available variables (ice radius and penetration), we can solve the collision force equation:

$$\boldsymbol{F = P_o(\ \pi\ (2R\,p - p^2)\ )^{(ex+1)}} \qquad (6)$$

Using this equation in the software allows for the calculation of collision force at each time step in the simulation. As the penetration (p) increases, so does the collision force acting on both the ship and the ice. This increasing force tends to slow the movement of the ice piece until it stops. At this point the force is turned off and the simulation is over.

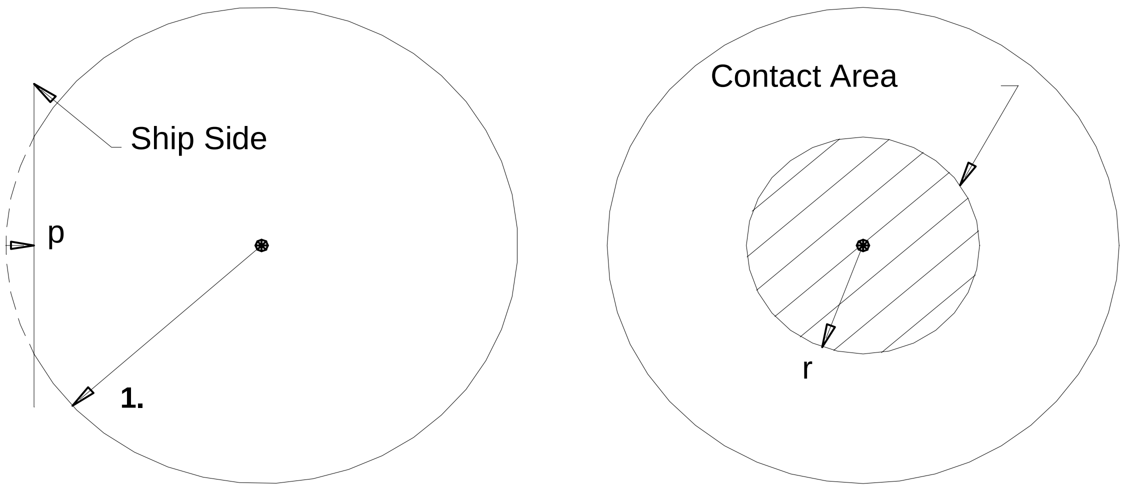


Figure 4. Shape of the contact area.

One small source of error in the simulation is related to the time step, since the integration is numerical. The only way to check when the collision force should be turned off (since the iceberg velocity would rarely equal precisely zero), is when the direction of the velocity changes. Thus, the collision force is still on for the first step after the berg stops. This error tends to give the berg a small initial velocity in the opposite direction.

It should be noted that the density of ice was assumed to be 922.5 kg/m^3. At this stage in the model development, it has been assumed that effects of an elastic layer are negligible and so modeling this has been ignored.

2.3. Ship Model

Like the iceberg, the ship was modeled in the software's two-dimensional environment as a three-dimensional entity. The body view of the ship was shown on the screen (refer to Figure 3). Forces were applied to the centre of gravity to allow it realistic motions in three degrees of freedom – translation in sway and heave, and rotation in roll. In order to properly simulate the vessel's roll characteristics, a moment was added to the centre of gravity of the ship – the righting moment. Thus, when the collision occurred and the ship rolled slightly (due to the moment arm between the application point of the force and the ship's centre of gravity), the righting moment would to bring the ship back into the upright equilibrium position.

During collision with a moving iceberg, the model assumes that the contact area does not extend beyond the edge of the ship's bilge curvature (see Figure 5). This assumption is reasonable since the collisions occur more with relatively smaller icebergs, and hence have smaller relative penetrations. Larger bergs would penetrate more deeply into the side shell of the ship. In some cases a small amount of penetration occurs into the bilge, but it is ignored for simplicity.

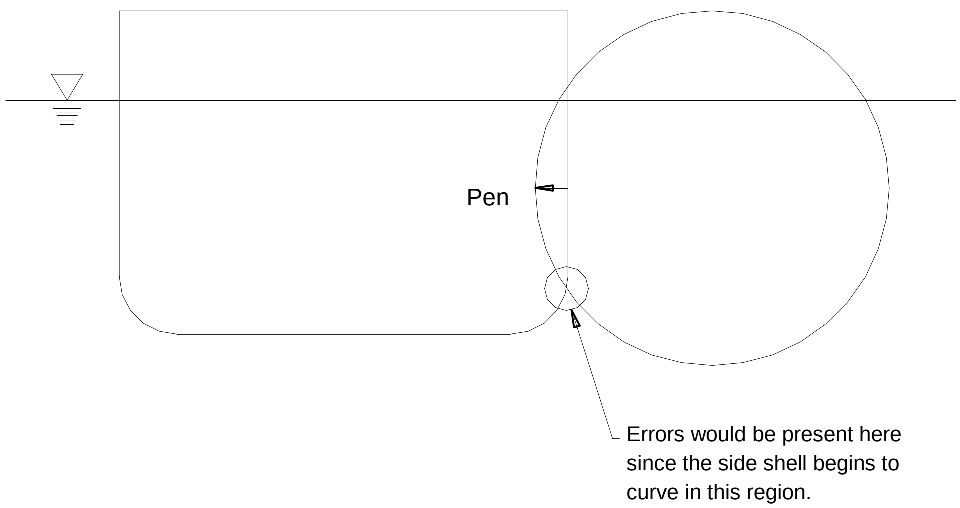


Figure 5. Assumed extent of contact.

The following figures (Figures 6 to 9) show images of the working model screen during a simulation which was run for a 10 ktonne ship impacted by a 100 tonne iceberg with a pressure-area exponent of –0.7 and moving at a velocity of 2 m/s. Figure 6 was taken immediately after first contact. Figures 7, 8, 9 show the load, contact area and penetration increasing and finally, Figure 10 is immediately after the collision has stopped. All input parameters are shown in the individual text boxes of the screen. The particulars for all ships and icebergs simulated are given in Table 3 and 4 respectively.

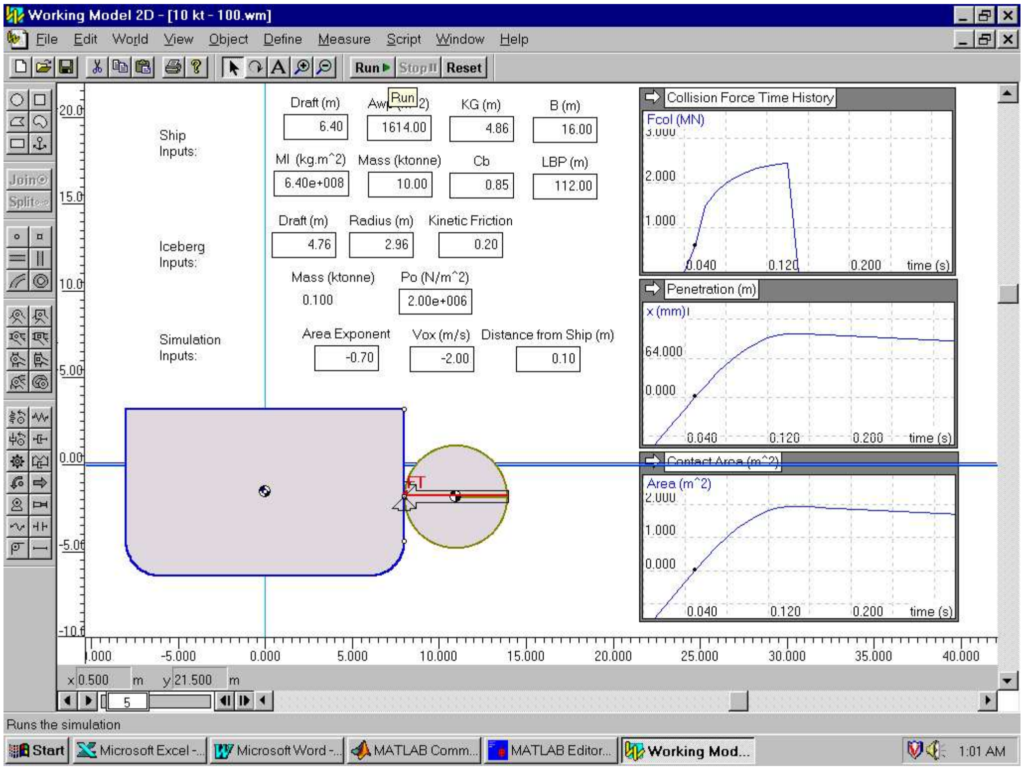


Figure 6. Start of simulation.

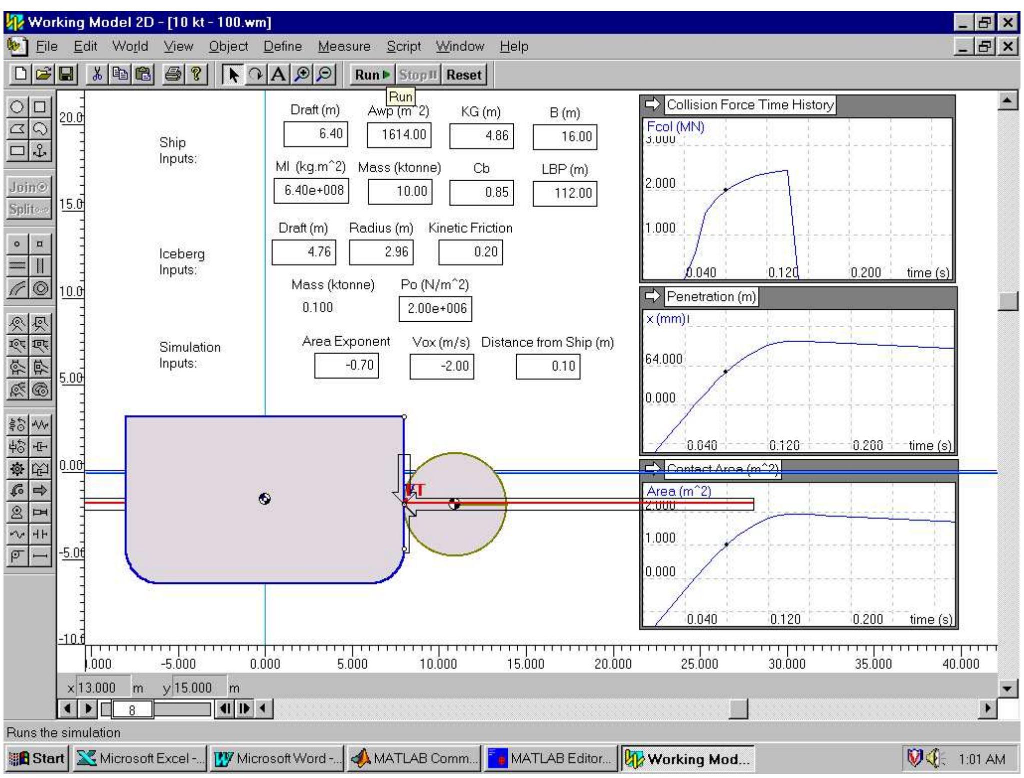


Figure 7. Intermediate step in simulation.

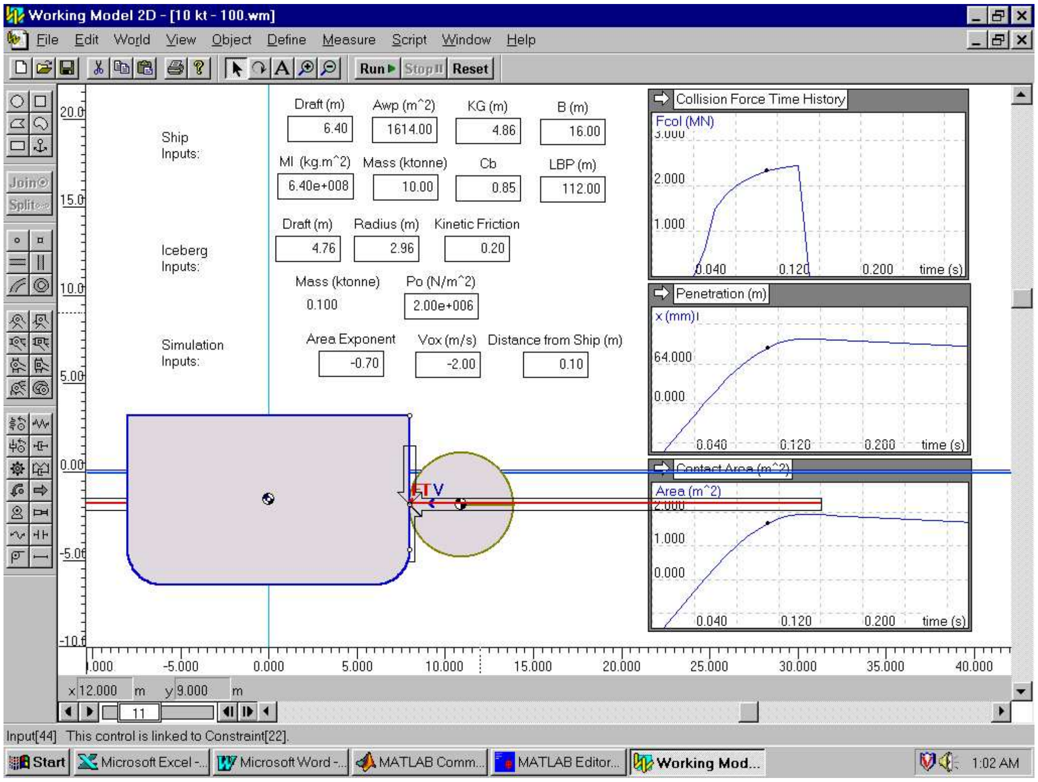


Figure 8. Intermediate step in simulation.

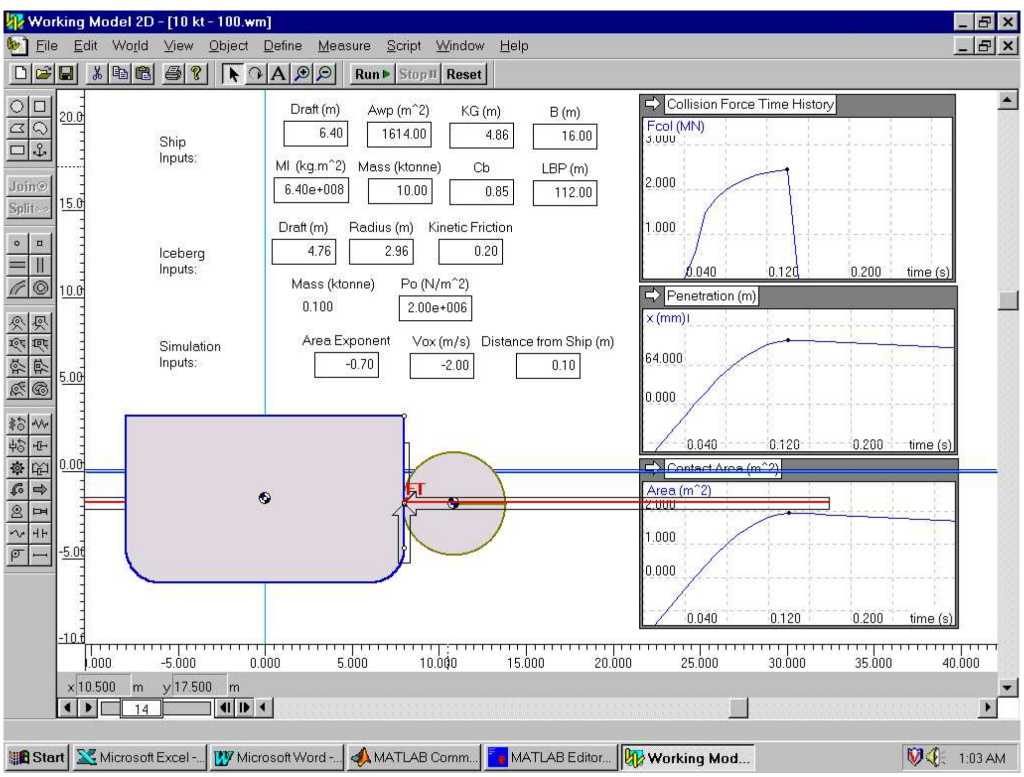


Figure 9. Intermediate step in simulation.

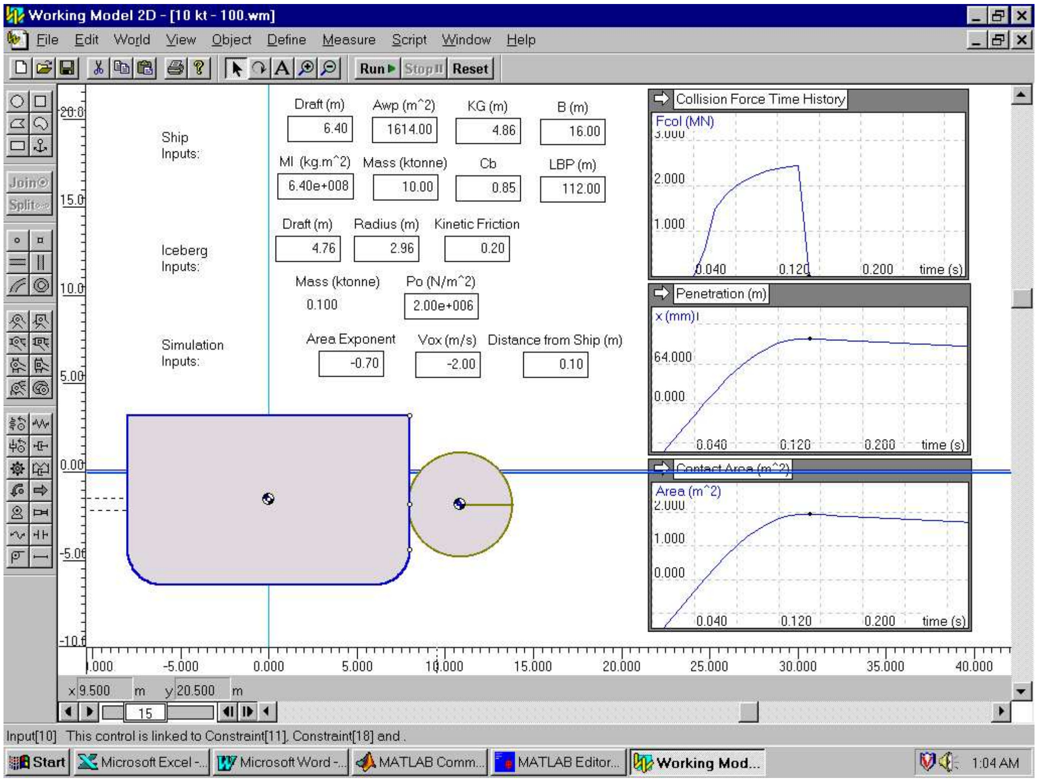


Figure 10. Immediately after end of collision.

Table 3. Particulars for all ships simulated.

Δ (kt)	10	20	40	100
T (m)	6.40	8.07	10.16	13.79
A_{wp} (m^2)	1614	2561	4066	7490
KG (m)	4.86	6.12	7.72	10.47
B (m)	16.00	20.16	25.41	34.48
MI (kg m^2)	6.40 E8	2.03 E9	6.45 E9	2.97 E10
C_B	0.85	0.85	0.85	0.85
LBP	112.0	141.1	177.8	241.4

Table 4. Table 2.2 **– Particulars for all icebergs simulated.**

Δ (t)	50	100	1000	5000	10000
T (m)	3.78	4.76	10.25	17.53	22.08
R (m)	2.35	2.96	6.37	10.90	13.73
μ_k	0.2	0.2	0.2	0.2	0.2

3. SIMULATION RESULTS AND MEANING

3.1. Summary of Simulation Results

A total of 150 simulations were run, based on the matrix outlined in Table 2. Time history data was collected and stored in a separate data file for each simulation. Plots of this data are provided in Appendix A for collision force, penetration and contact area. It can be seen in a number of the plots in Appendix A that there is a slight reduction in force immediately after Fmax has been reached. This error originates from the integration time step inherent in the software and is deemed to be of small enough magnitude to be ignored.

From these time histories, the maximum values were obtained for each simulation – Fmax, Penmax, and ConAreamax are the maximum force, penetration and contact area respectively. Tables 3.1, 3.2, and 3.3 provide the values of Fmax, Penmax, and ConAreamax for all simulations run. A zero shown in the tables indicates that this combination of parameters was not simulated.

An extensive number of plots were created from this data set of maximum force, penetration and contact area. A matrix of all possibilities was created to determine which plots would provide the most useful and interesting display of the information. Four sets of plots were produced based on this:

1. **Fmax, Penmax and ConAreamax** vs. **Ice Velocity** for a family of **area exponent** curves (ie. for all combinations of ship and ice displacements),
2. **Fmax, Penmax and ConAreamax** vs. **Ice Velocity** for a family of **ship displacement** curves (ie. for all combinations of ice displacements and area exponents),
3. **Fmax, Penmax and ConAreamax** vs. **Area Exponent** for a family of **ice velocity** curves (ie. for all combinations of ship and ice displacements), and
4. **Fmax, Penmax and ConAreamax** vs. **Area Exponent** for a family of **ship displacement** curves (ie. for all combinations of ice displacements and ice velocities).

These plots are given correspondingly in Appendices B, C, D and E.

3.2. Discussion of Results

Examination of the plots provided in Appendices B, C, D and E reveals numerous noteworthy trends. In Appendix B, we can see a "crossover" point in many plots where the contact area has grown to above 1 m^2. This crossover point seems only to occur in combinations of smaller ships and icebergs and can be reasonably explained by the fact that for larger bergs, a smaller penetration is required to produce a corresponding contact area greater than 1 m^2. The crossover point, though detectable, is not precisely a single point. This small source of error is also attributable to the integration time stepping of the software.

For the first three plots of Fmax the crossover point can be seen, with the same pattern emerging each time. The line representing the pressure area exponent 0.0 marks the lower boundary of the data to the left of the crossover point but switches to mark the upper bound on the data to the right of the crossover point. Similarly, the exponent –0.7 marks the upper bound left of the crossover point and switches to the lower bound on the right. Lines for all other exponents fall (in order) between these two. In cases where no crossover point exists, the pressure area exponent 0.0 always marks the upper bound and –0.7 always marks the lower.

For the plots of penetration and contact area, cases involving 100 t icebergs tend to converge to a single point at a velocity of 2 m/s. This appears to be a crossover point as well, since the pressure area exponent 0.0 marks the upper bound for smaller bergs (50 and 100 t) and switches to mark the lower bound on larger bergs (greater than 100 t).

Plots shown in Appendix C and E show that there is little variation in force between different ship displacements plotted on the same axis as functions of velocity and pressure area exponent respectively. This trend indicates that Fmax, Penmax and ConAreamax are not dependent on ship displacement.

Table 5. Maximum force values from all simulations [MN].

		50 tonne iceberg			100 tonne iceberg			1000 tonne iceberg			5000 tonne iceberg			10000 tonne iceberg		
	V [m/s]	0.5	1.0	2.0	0.5	1.0	2.0	0.5	1.0	2.0	0.5	1.0	2.0	0.5	1.0	2.0
Ship 1	Exp= 0.0	0.61	1.22	2.45	0.96	1.92	3.84									
	Exp=-0.1	0.62	1.22	2.36	0.97	1.88	3.62									
	Exp=-0.3	0.69	1.23	2.20	1.02	1.80	3.19									
	Exp=-0.5	0.80	1.30	2.06	1.11	1.77	2.81									
	Exp=-0.7	1.03	1.43	1.98	1.29	1.77	2.44									
Ship 2	Exp= 0.0				0.97	1.92	3.85	4.36	8.72	17.44						
	Exp=-0.1				0.98	1.88	3.65	4.08	7.87	15.19						
	Exp=-0.3				1.02	1.81	3.19	3.55	6.29	11.13						
	Exp=-0.5				1.11	1.78	2.81	3.05	4.85	7.70						
	Exp=-0.7				1.28	1.77	2.45	2.59	3.57	4.92						
Ship 3	Exp= 0.0				0.97	1.91	3.88	4.41	8.83	17.65	12.27	24.55	49.08			
	Exp=-0.1				0.98	1.87	3.61	4.13	7.97	15.36	10.89	21.00	40.49			
	Exp=-0.3				1.02	1.82	3.21	3.59	6.36	11.24	8.33	14.75	26.10			
	Exp=-0.5				1.11	1.78	2.82	3.08	4.89	7.76	6.09	9.67	15.35			
	Exp=-0.7				1.28	1.79	2.45	2.61	3.60	4.95	4.18	5.76	7.93			
Ship 4	Exp= 0.0							4.45	8.90	17.76	12.76	25.51	51.01	19.73	39.46	78.93
	Exp=-0.1							4.16	8.03	15.46	11.29	21.78	41.99	17.07	32.92	63.49
	Exp=-0.3							3.61	6.40	11.31	8.60	15.23	26.95	12.32	21.81	38.60
	Exp=-0.5							3.09	4.91	7.80	6.25	9.92	15.75	8.36	13.27	21.07
	Exp=-0.7							2.62	3.60	4.96	4.26	5.86	8.08	5.21	7.17	9.88

Table 6. Maximum penetration values from all simulations [mm].

		50 tonne iceberg			100 tonne iceberg			1000 tonne iceberg			5000 tonne iceberg			10000 tonne iceberg		
	V [m/s]	0.5	1.0	2.0	0.5	1.0	2.0	0.5	1.0	2.0	0.5	1.0	2.0	0.5	1.0	2.0
Ship 1	Exp= 0.0	20.50	41.39	82.95	25.81	51.63	103.3									
	Exp=-0.1	18.36	38.92	81.52	24.03	50.13	103.9									
	Exp=-0.3	14.64	33.74	77.74	20.39	46.20	104.6									
	Exp=-0.5	10.92	28.54	72.09	16.48	41.91	105.8									
	Exp=-0.7	7.34	22.25	64.90	12.61	35.82	104.6									
Ship 2	Exp= 0.0				25.99	51.70	103.5	54.4	108.9	217.8						
	Exp=-0.1				24.23	50.25	104.8	55.2	114.5	237.6						
	Exp=-0.3				20.63	46.67	104.6	56.8	128.3	290.1						
	Exp=-0.5				16.65	42.40	106.3	58.2	146.8	370.2						
	Exp=-0.7				12.02	36.00	105.7	59.4	172.8	502.1						
Ship 3	Exp= 0.0				26.02	51.34	104.3	55.1	110.3	220.5	89.6	179.2	358.3			
	Exp=-0.1				24.26	50.03	103.7	56.0	116.1	240.6	96.0	199.0	412.9			
	Exp=-0.3				20.66	47.15	105.6	57.6	130.4	294.4	112.2	253.6	573.1			
	Exp=-0.5				16.68	42.58	106.7	59.2	149.5	376.2	135.4	341.4	860.0			
	Exp=-0.7				12.05	37.17	105.1	60.6	176.6	511.2	170.9	497.0	1443			
Ship 4	Exp= 0.0							55.6	111.2	221.9	93.2	186.3	372.5	114.4	228.7	457.5
	Exp=-0.1							56.4	117.1	242.4	100.0	207.3	430.0	125.6	260.5	540.4
	Exp=-0.3							58.1	131.5	297.0	117.4	265.4	599.8	155.7	351.9	795.4
	Exp=-0.5							59.8	150.8	380.1	142.6	359.4	905.5	202.5	510.4	1286
	Exp=-0.7							61.3	178.0	517.4	181.4	526.8	1531	281.7	818.8	2379

Table 7. Maximum contact areas from all simulations [m^2].

		50 tonne iceberg			100 tonne iceberg			1000 tonne iceberg			5000 tonne iceberg			10000 tonne iceberg		
	V [m/s]	0.5	1.0	2.0	0.5	1.0	2.0	0.5	1.0	2.0	0.5	1.0	2.0	0.5	1.0	2.0
Ship 1	Exp= 0.0	0.303	0.611	1.225	0.480	0.960	1.920									
	Exp=-0.1	0.271	0.575	1.204	0.447	0.932	1.932									
	Exp=-0.3	0.216	0.498	1.148	0.379	0.859	1.945									
	Exp=-0.5	0.161	0.421	1.065	0.306	0.780	1.968									
	Exp=-0.7	0.108	0.328	0.958	0.234	0.666	1.945									
Ship 2	Exp= 0.0				0.483	0.962	1.924	2.179	4.358	8.72	0.00	0.00	0.00	0.00	0.00	0.00
	Exp=-0.1				0.451	0.935	1.949	2.210	4.582	9.51	0.00	0.00	0.00	0.00	0.00	0.00
	Exp=-0.3				0.384	0.868	1.946	2.272	5.135	11.61	0.00	0.00	0.00	0.00	0.00	0.00
	Exp=-0.5				0.310	0.789	1.978	2.330	5.876	14.82	0.00	0.00	0.00	0.00	0.00	0.00
	Exp=-0.7				0.224	0.669	1.965	2.376	6.915	20.10	0.00	0.00	0.00	0.00	0.00	0.00
Ship 3	Exp= 0.0				0.484	0.955	1.941	2.205	4.416	8.83	6.14	12.27	24.54	0.00	0.00	0.00
	Exp=-0.1				0.451	0.930	1.928	2.240	4.648	9.63	6.57	13.63	28.28	0.00	0.00	0.00
	Exp=-0.3				0.384	0.877	1.965	2.306	5.217	11.78	7.68	17.37	39.25	0.00	0.00	0.00
	Exp=-0.5				0.310	0.792	1.984	2.370	5.985	15.06	9.27	23.38	58.90	0.00	0.00	0.00
	Exp=-0.7				0.224	0.691	1.954	2.423	7.070	20.46	11.70	34.04	98.83	0.00	0.00	0.00
Ship 4	Exp= 0.0							2.226	4.449	8.88	6.38	12.76	25.51	9.87	19.73	39.47
	Exp=-0.1							2.258	4.685	9.70	6.85	14.20	29.44	10.83	22.47	46.62
	Exp=-0.3							2.327	5.263	11.89	8.04	18.17	41.07	13.43	30.36	68.62
	Exp=-0.5							2.393	6.037	15.21	9.76	24.61	62.00	17.47	44.03	111.0
	Exp=-0.7							2.452	7.123	20.71	12.42	36.07	104.8	24.30	70.64	205.3

4. Analytical Collision Model

An analytical solution for the collision forces can be derived using the balance of energy. The assumption is that the kinetic energy is completely transformed into crushing.

$$\boldsymbol{F = P_o(\pi(2R\,p - p^2))^{(ex+1)}} \qquad (6)$$

where
- p : penetration
- Po : ice pressure constant
- ex: ice pressure exponent
- R: berg radius
- F: Force

To derive the energy equation a simplified version (simplifying the area function) is;

$$\boldsymbol{F_n = P_o(\pi(2R\,p))^{(1+ex)}} \qquad (7)$$

The crushing energy is :

$$\boldsymbol{E_{crush} = \int F\,dp}$$
$$\boldsymbol{= P_o\,/(2+ex)\;\;(2\pi R)^{(1+ex)}\quad p^{(2+ex)}} \qquad (8)$$

The kinetic energy is :

$$\boldsymbol{E_{kinetic} = {}^1/_2\, M_e\, V_n^{\,2}} \qquad (9)$$

where
- Me : effective mass (in this case: mass + added mass)
- Vn : normal velocity

By equating energies (equating equations (8) and (9)) and solving for p, we get;

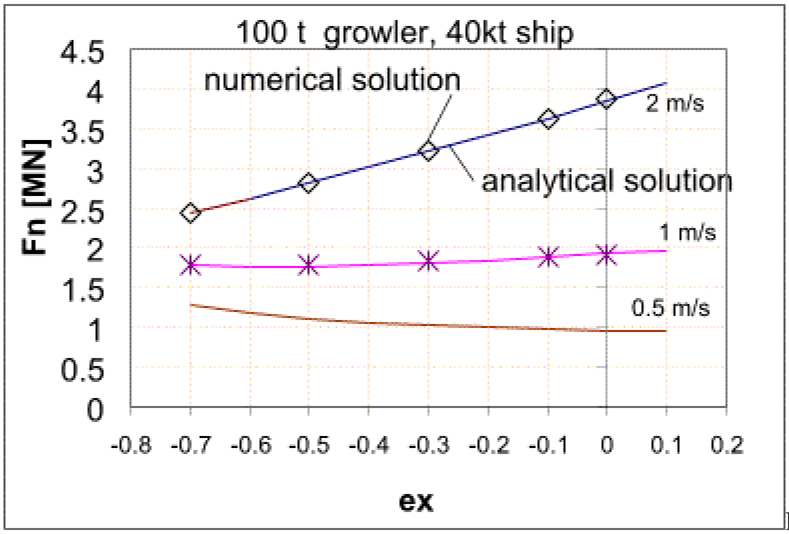
$$\boldsymbol{p = P_o\,/(2+ex)\;\;(2\pi R)^{(1+ex)}\quad p^{(2+ex)}} \qquad (8)$$

substituting (8) into (7) and collecting terms given an expression of the force;

$$F_n = Po^{\frac{1}{2+ex}}\,[\pi\,(2+ex)\,R\,M_e]^{mex}\;V_n^{2\,mex} \qquad (9)$$

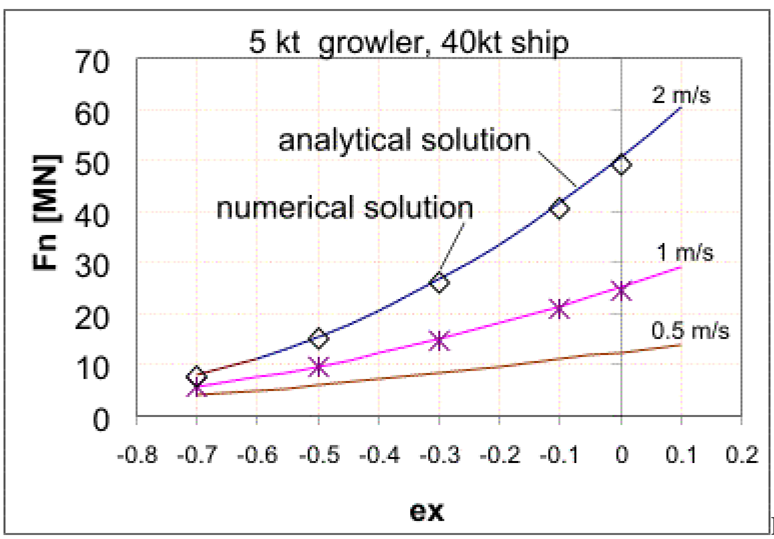
where
- mex = (1+ex)/(2+ex)

The analytical results from equation (9) compare favourably to the numerical results, as illustrated in Figures 11 and 12.



Po=2Mpa

Figure 11. Analytical vs numerical solution for small berg.



Po=2Mpa

Figure 12 Analytical vs numerical solution for medium berg.

5. CONCLUSIONS AND RECOMMENDATIONS

A model has been developed in Working Model 2D software for simulating transverse collisions between ships and icebergs. Results from the simulations show that a crossover point exists in situations with smaller ship-iceberg combinations. This crossover point represents the point at which the contact area reaches 1 m^2. Beyond this point, ice with a lower pressure area exponent would tend to produce larger hull forces than exponents with negative values under the same conditions. The significance of this issue can also be seen in Figures 11 and 12, which show small collisions to be insensitive to the ice pressure exponent. In this context small collisions are collisions that involve contact areas of about 1 m^2, and have forces of less than ~3 MN.

It has also been observed that ships of differing size do not affect the forces developed during ship-ice collisions where then ship is stationary and the ice is moving.

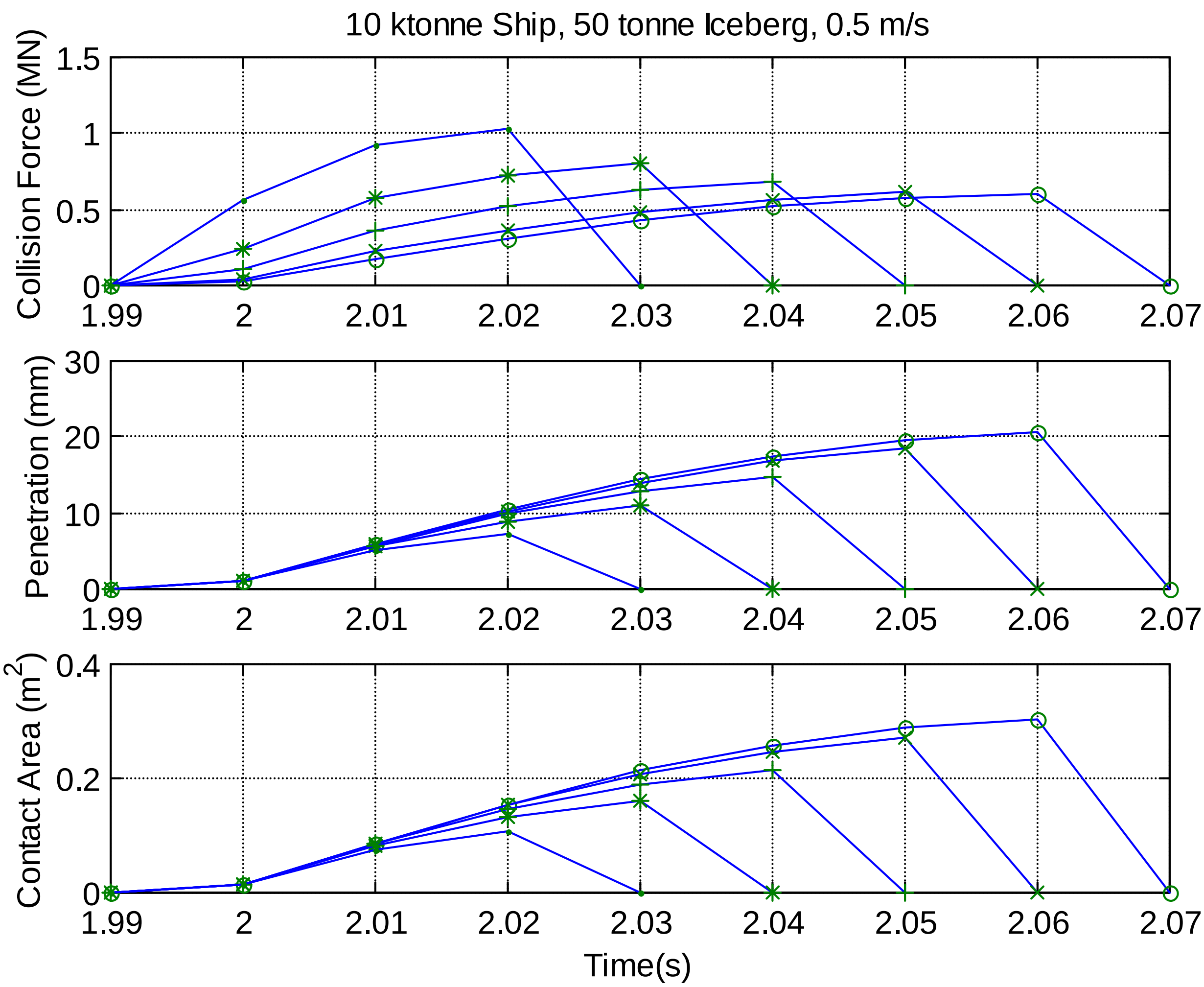
Recommendations for future work include the addition of wave motions to the simulation. This would allow for more realistic iceberg and ship motions, as well as possibly causing greater driving forces to act on the system. It is recommended that more realistic ice shapes be used in future versions of this work. While a perfectly spherical iceberg simplifies the problem considerably, it would be of value to determine the effect of varying shape on the collision forces developed. For the current model, viscous fluid damping has been ignored. This is another simplification that should be improved in future versions of this model, so that hydrodynamics can be more accurately modeled.

Appendix A:

Time History Plots of Simulations

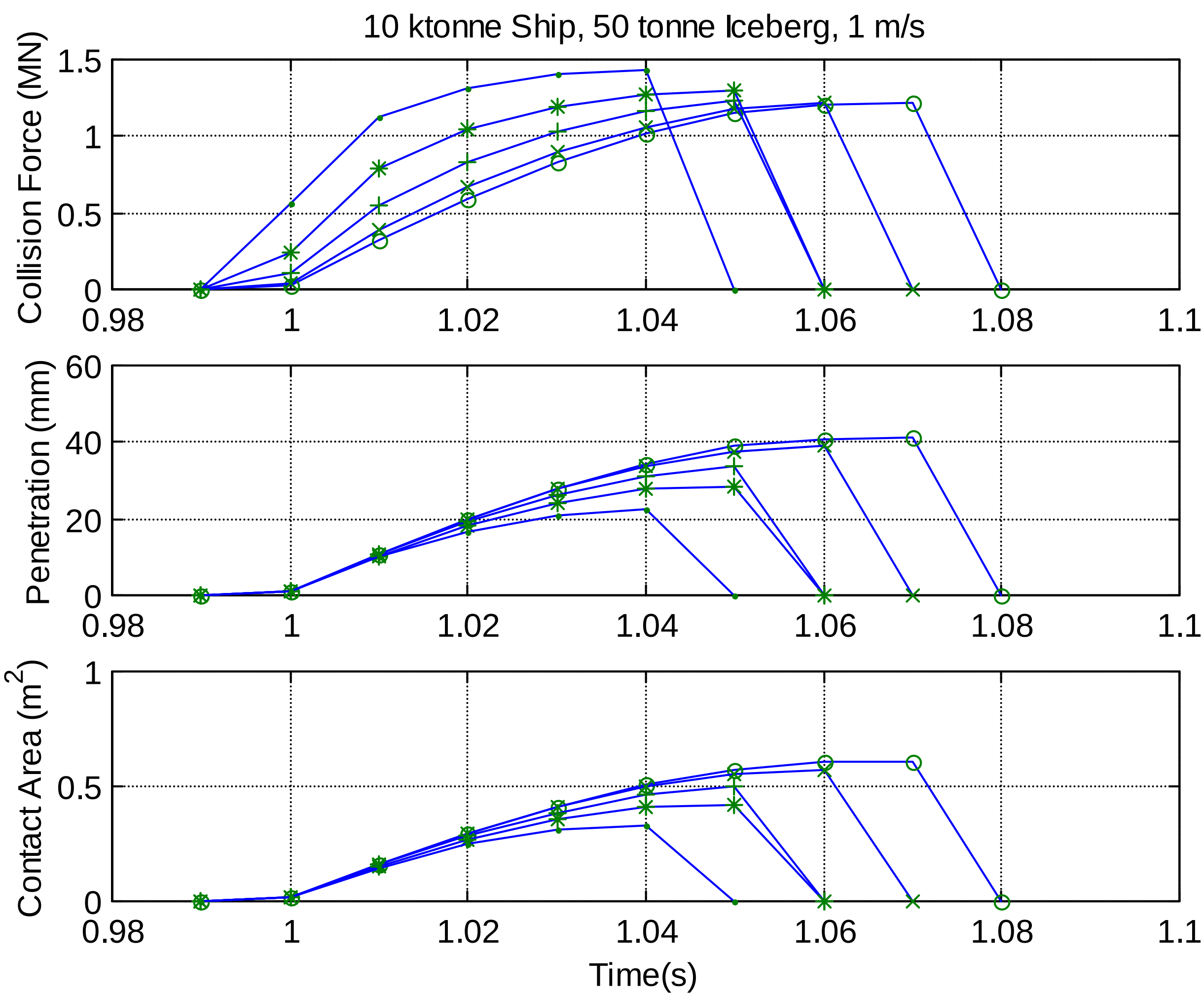
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



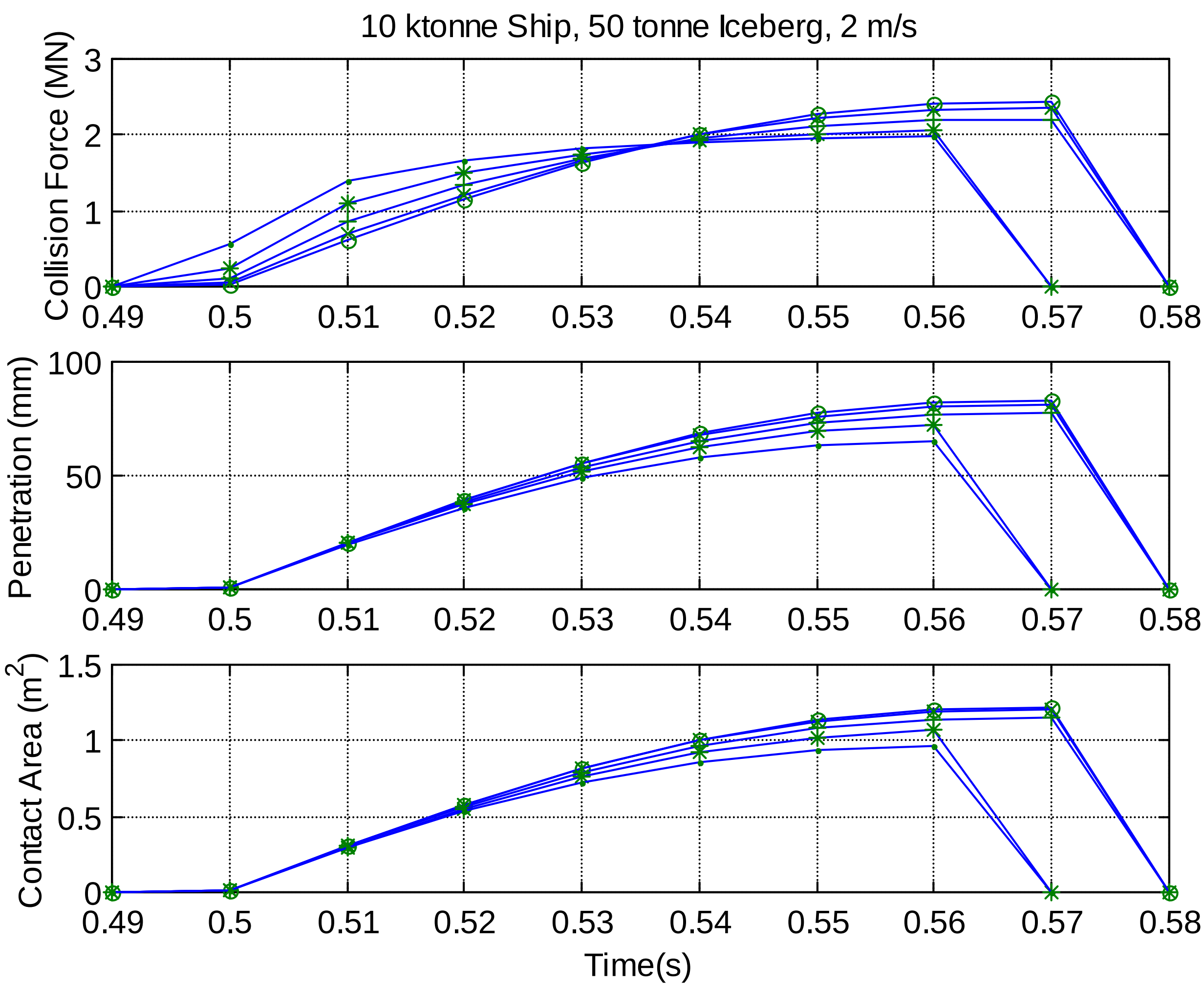
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



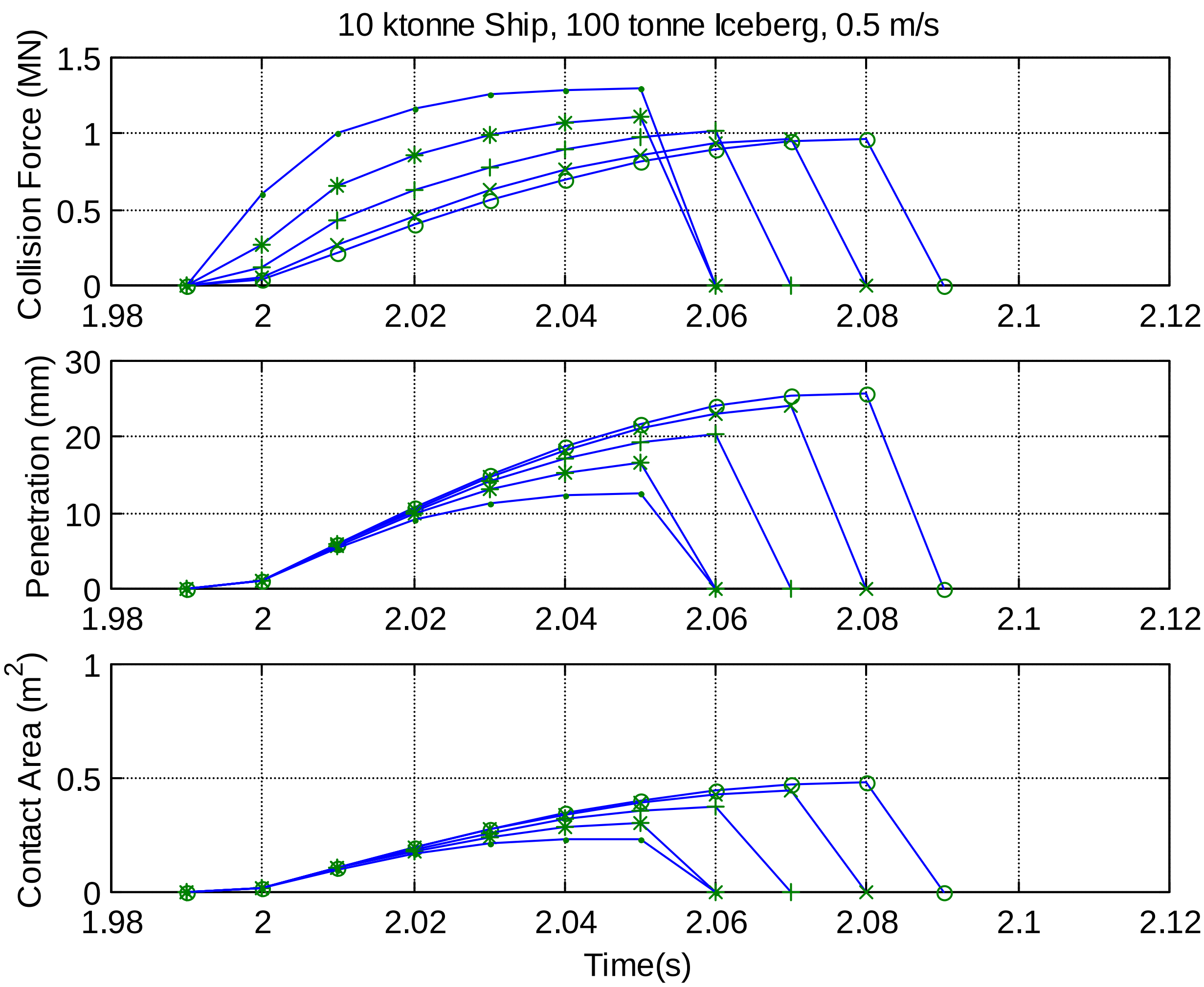
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



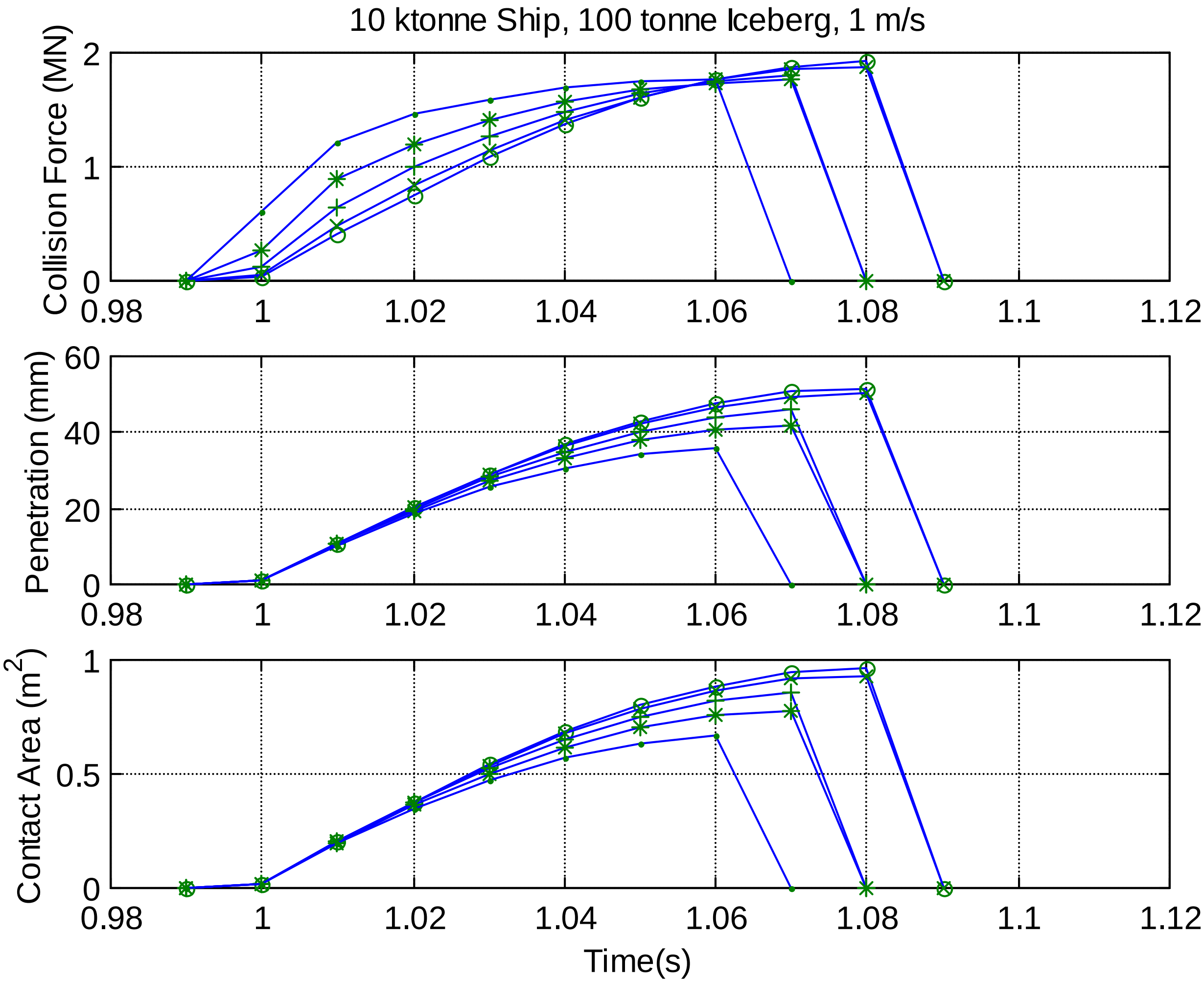
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



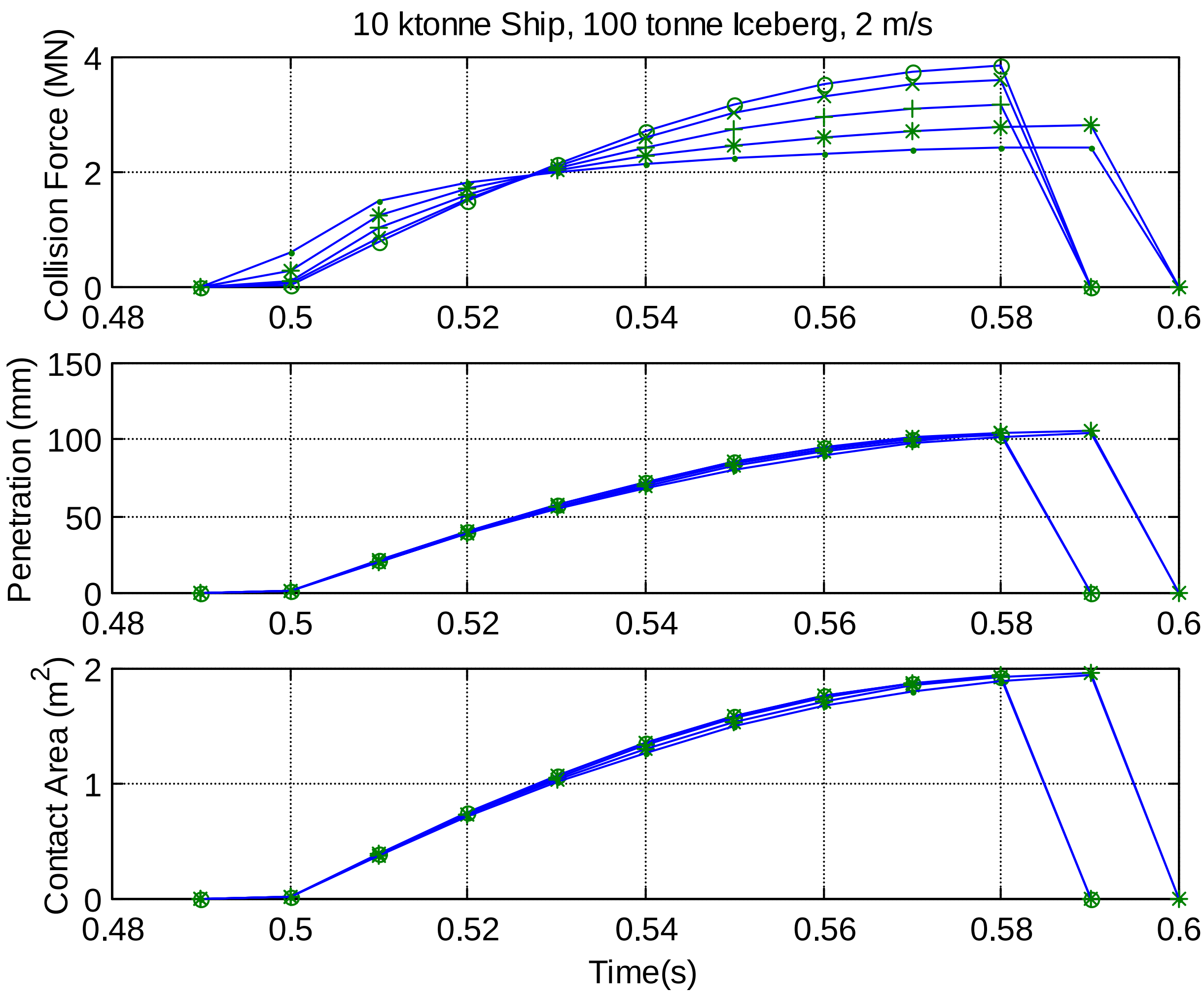
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



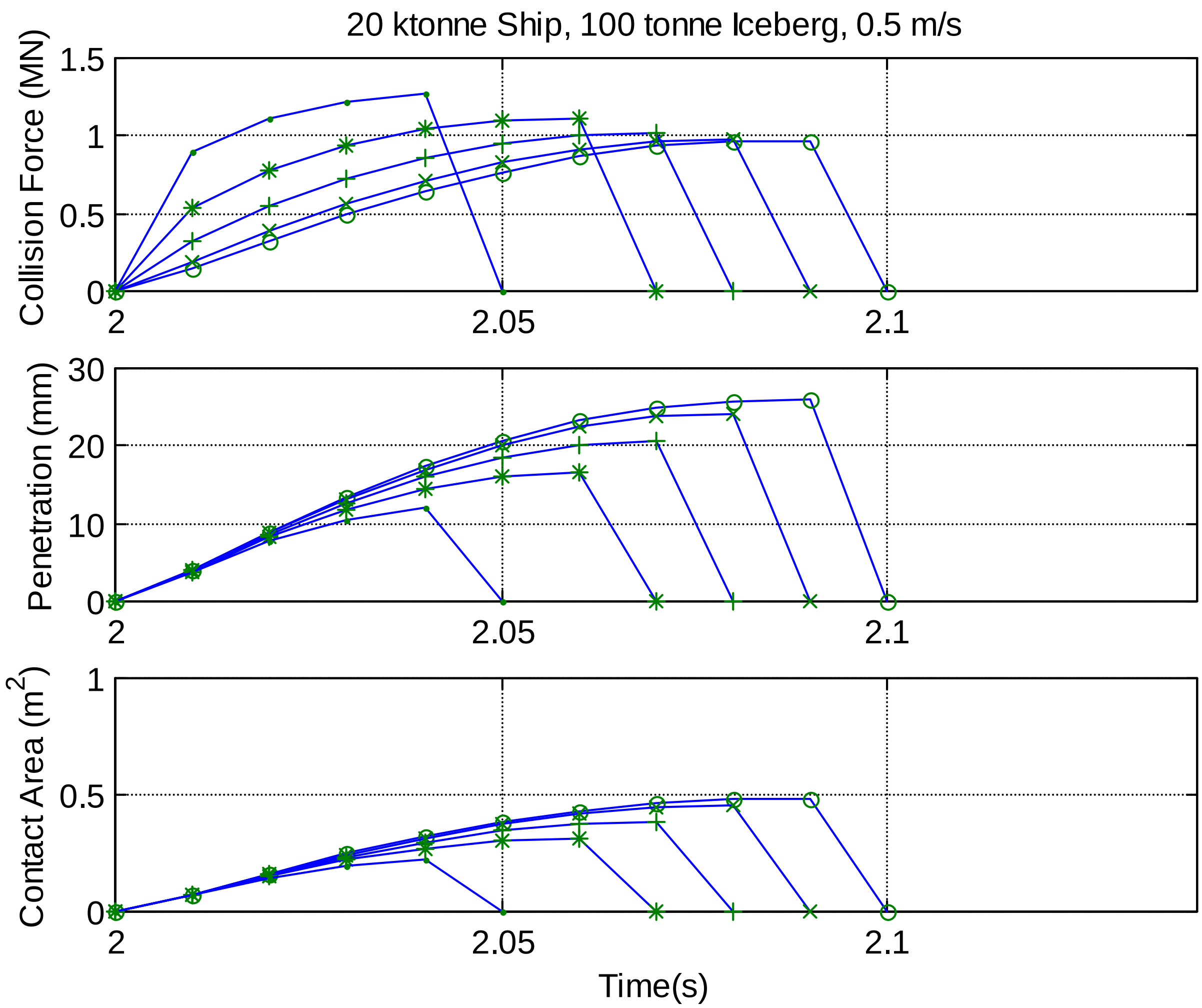
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



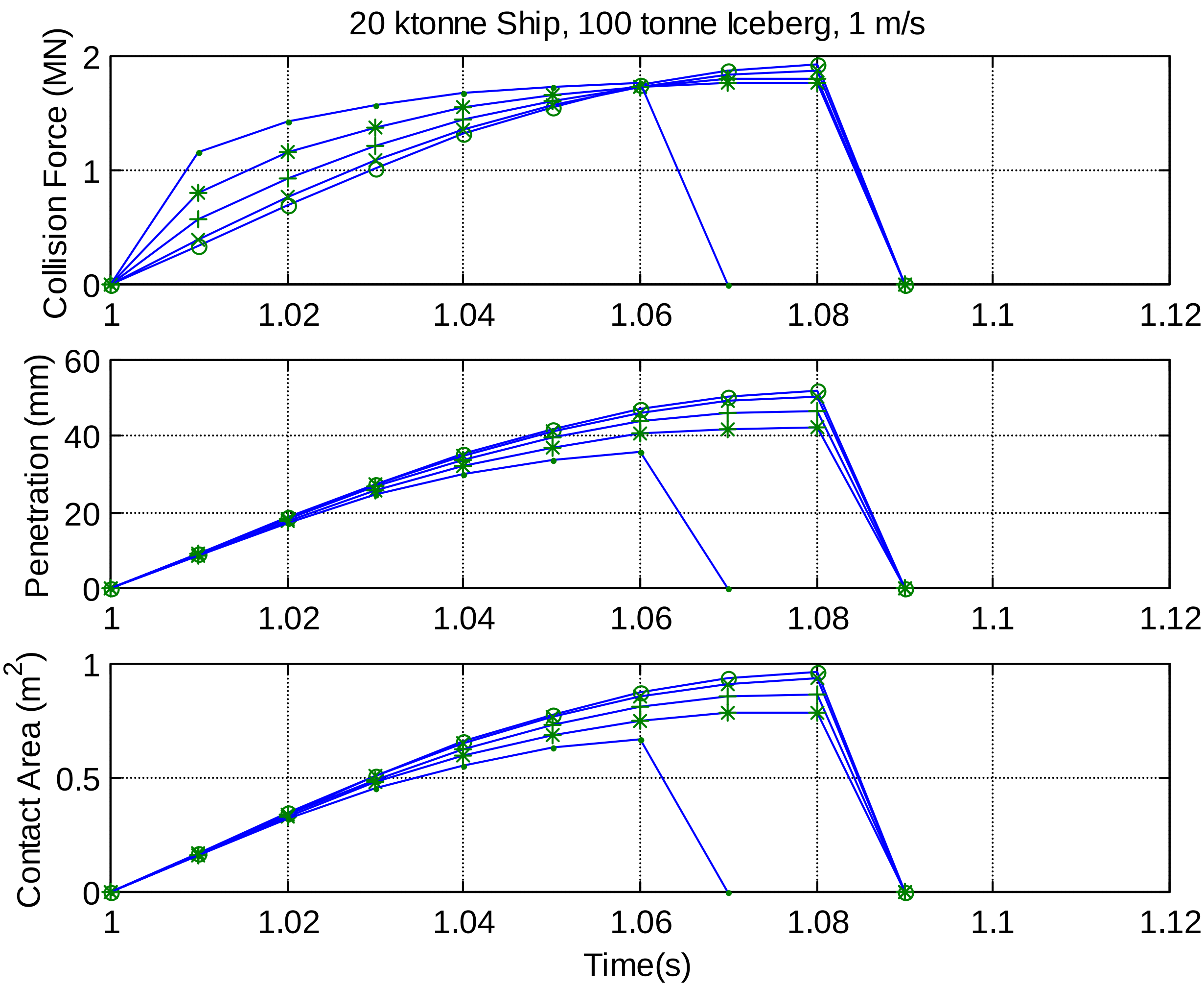
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



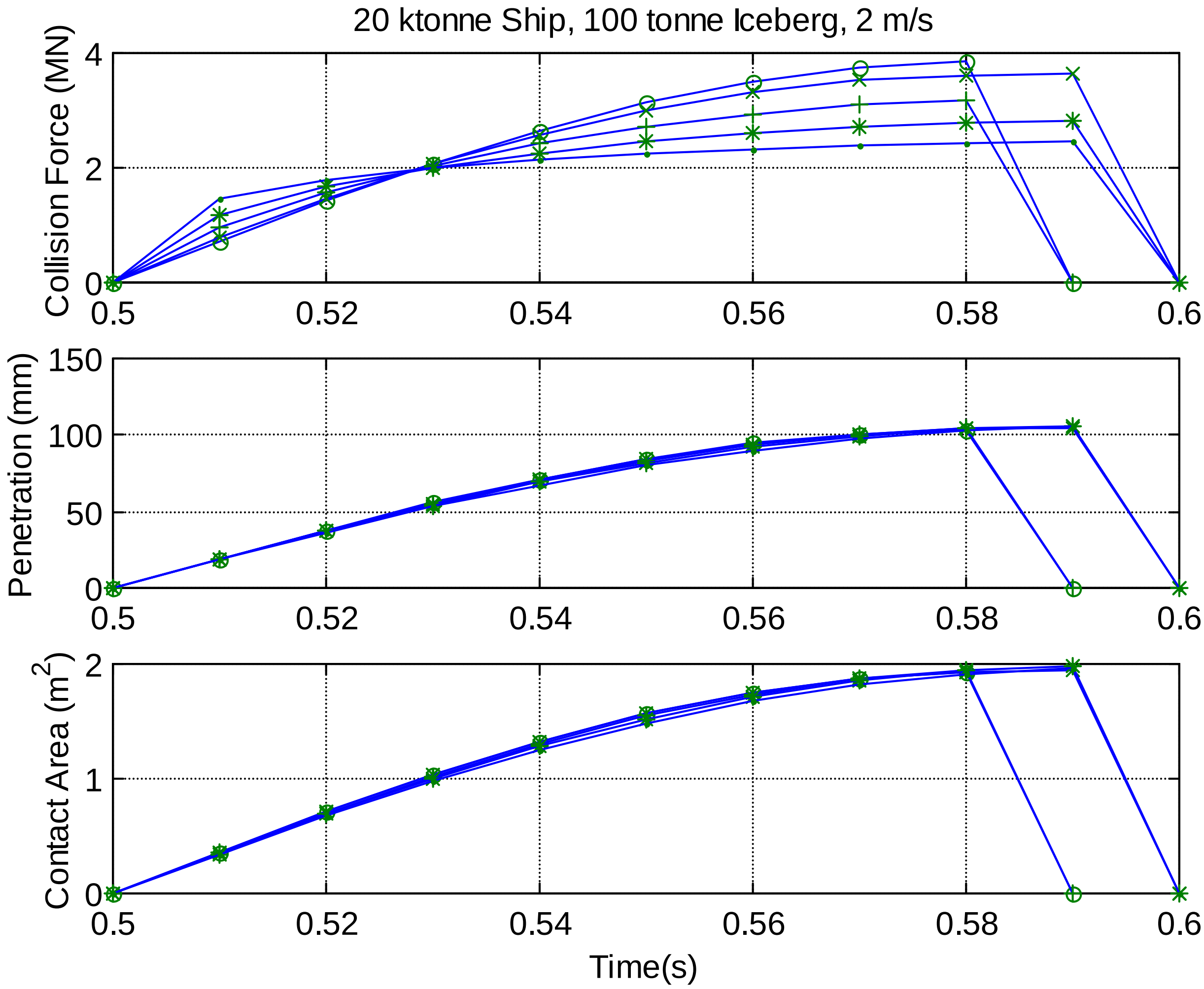
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



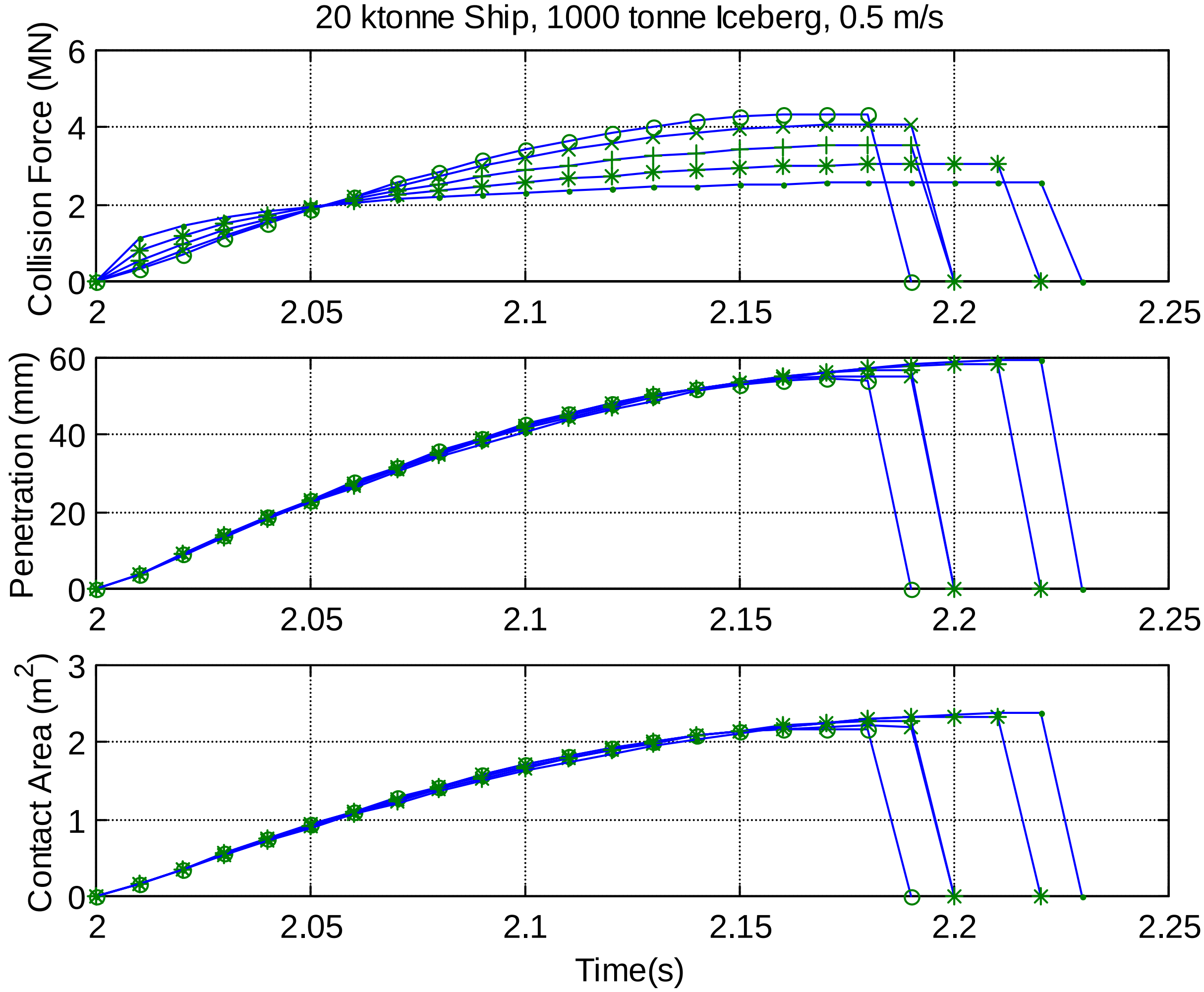
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



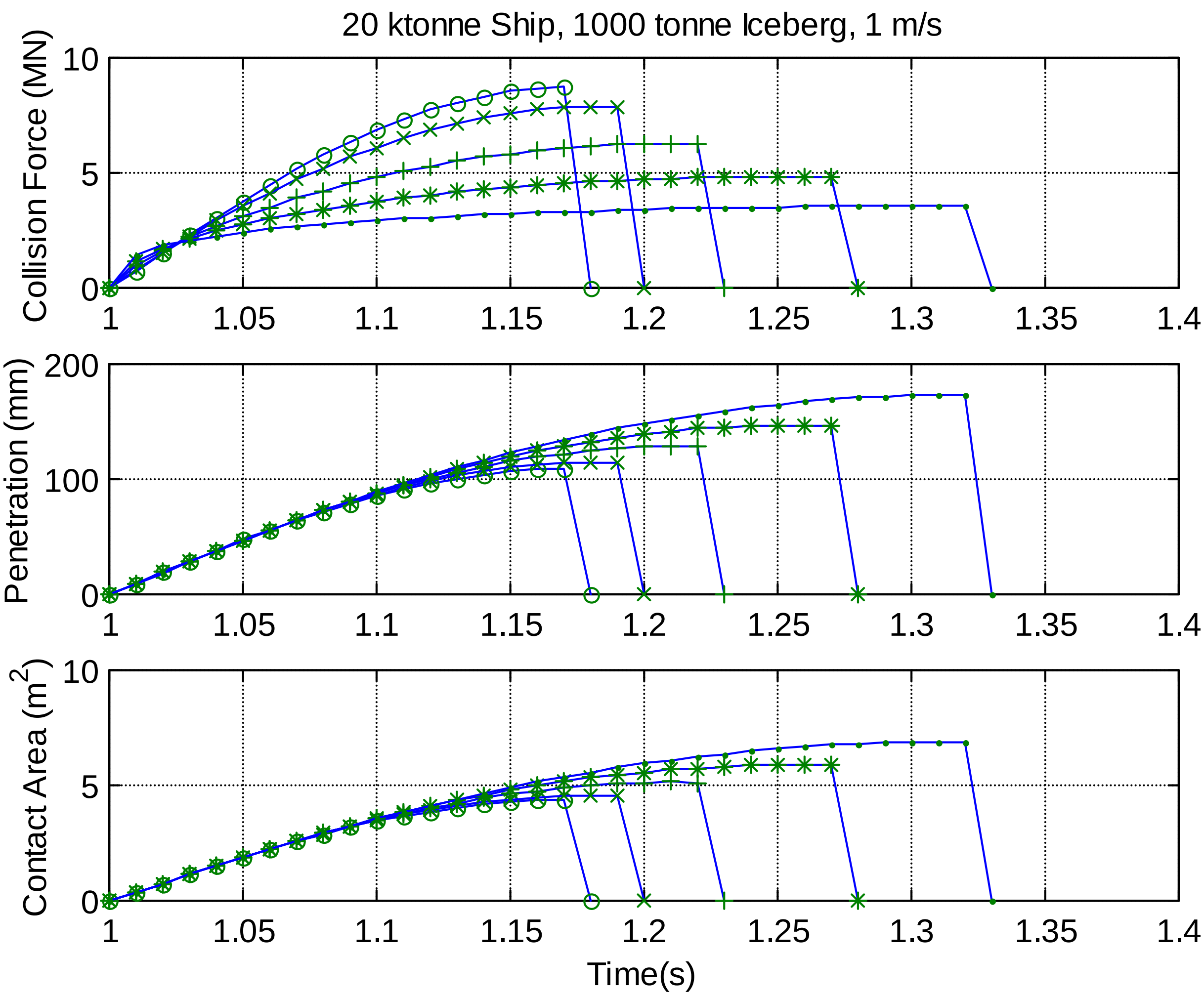
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



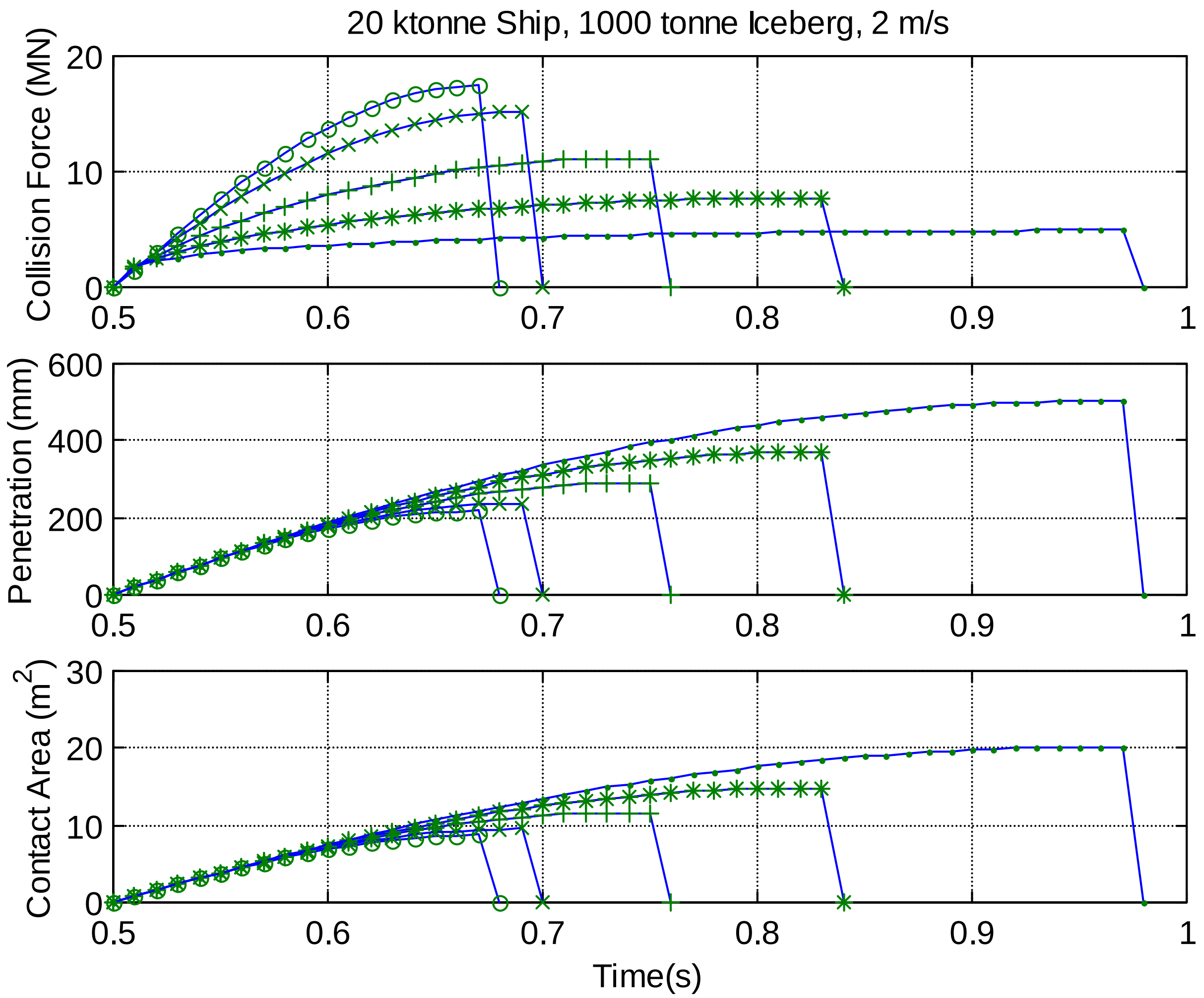
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



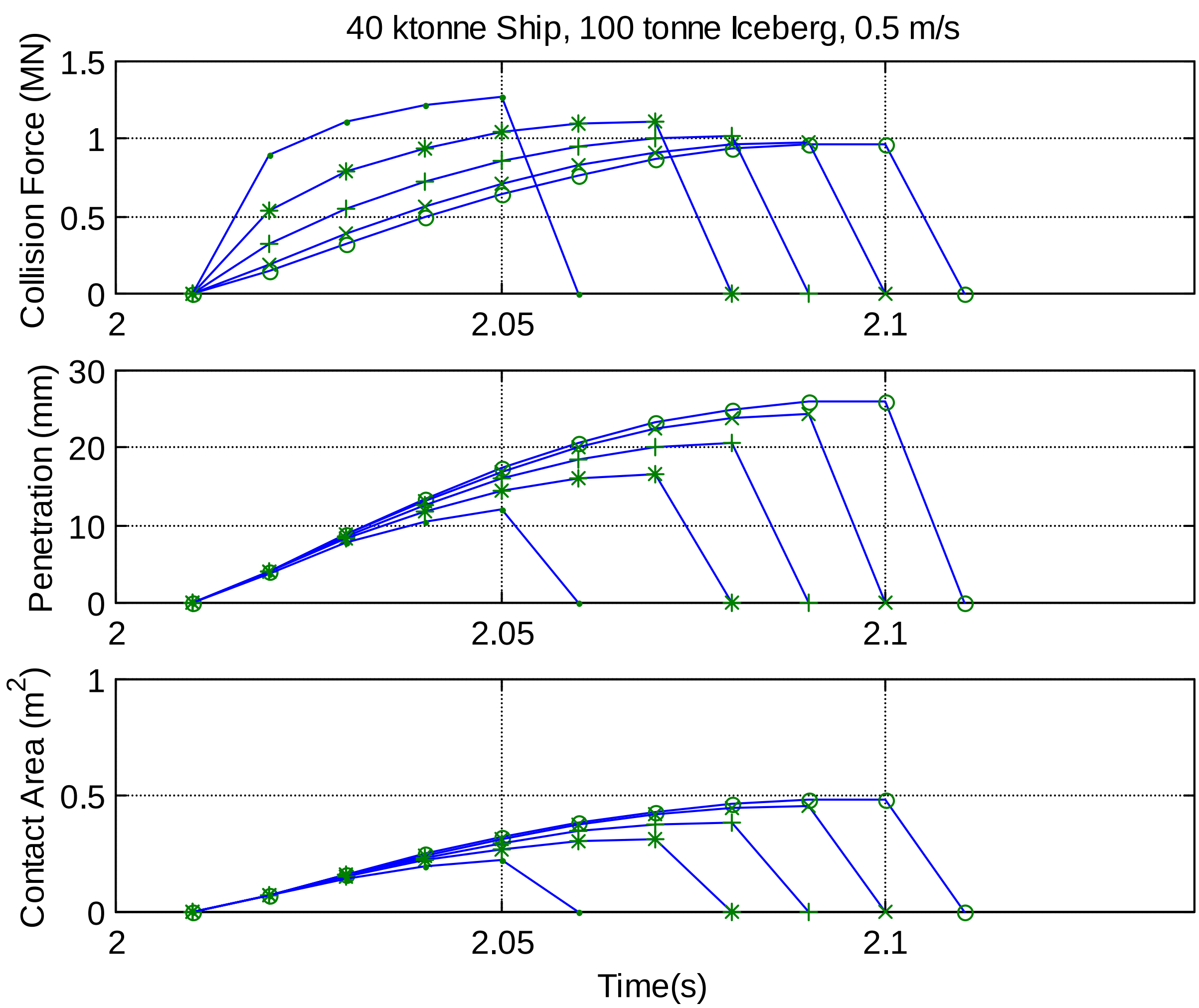
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



Legend:

Symbol	Pressure Area Exponent
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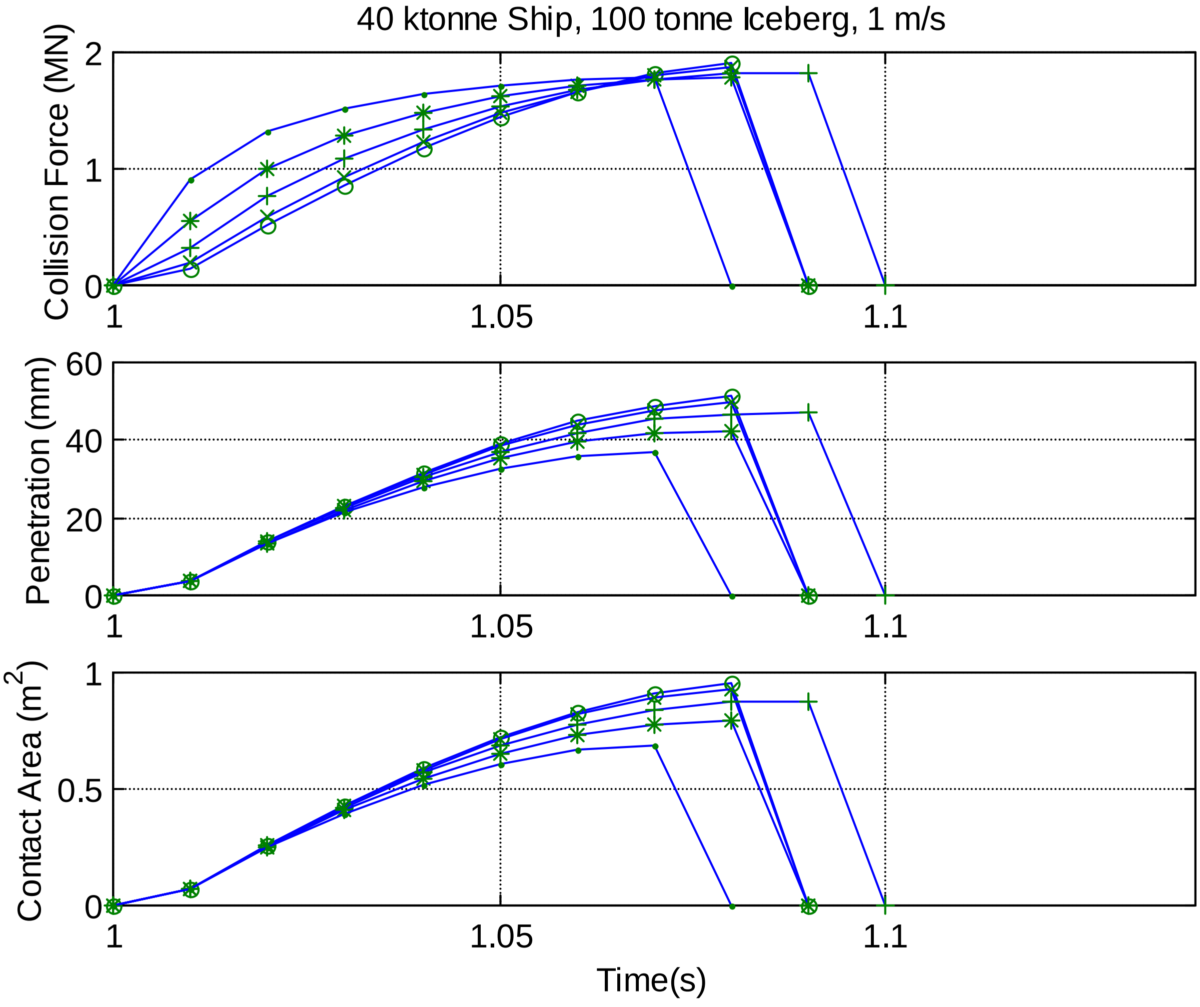
X	-0.1
+	-0.3
*	-0.5
•	-0.7



Legend:

Symbol	Pressure Area Exponent
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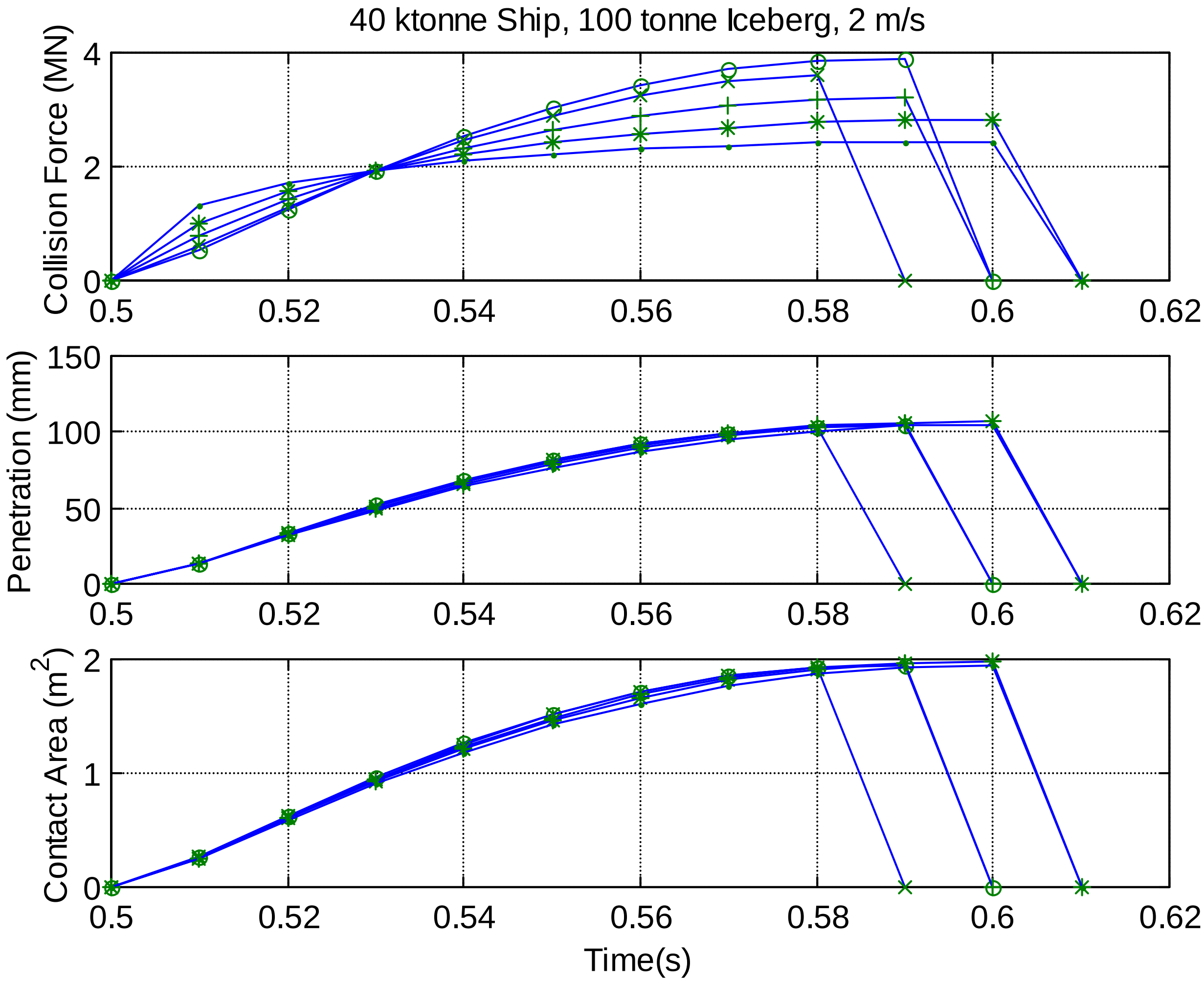
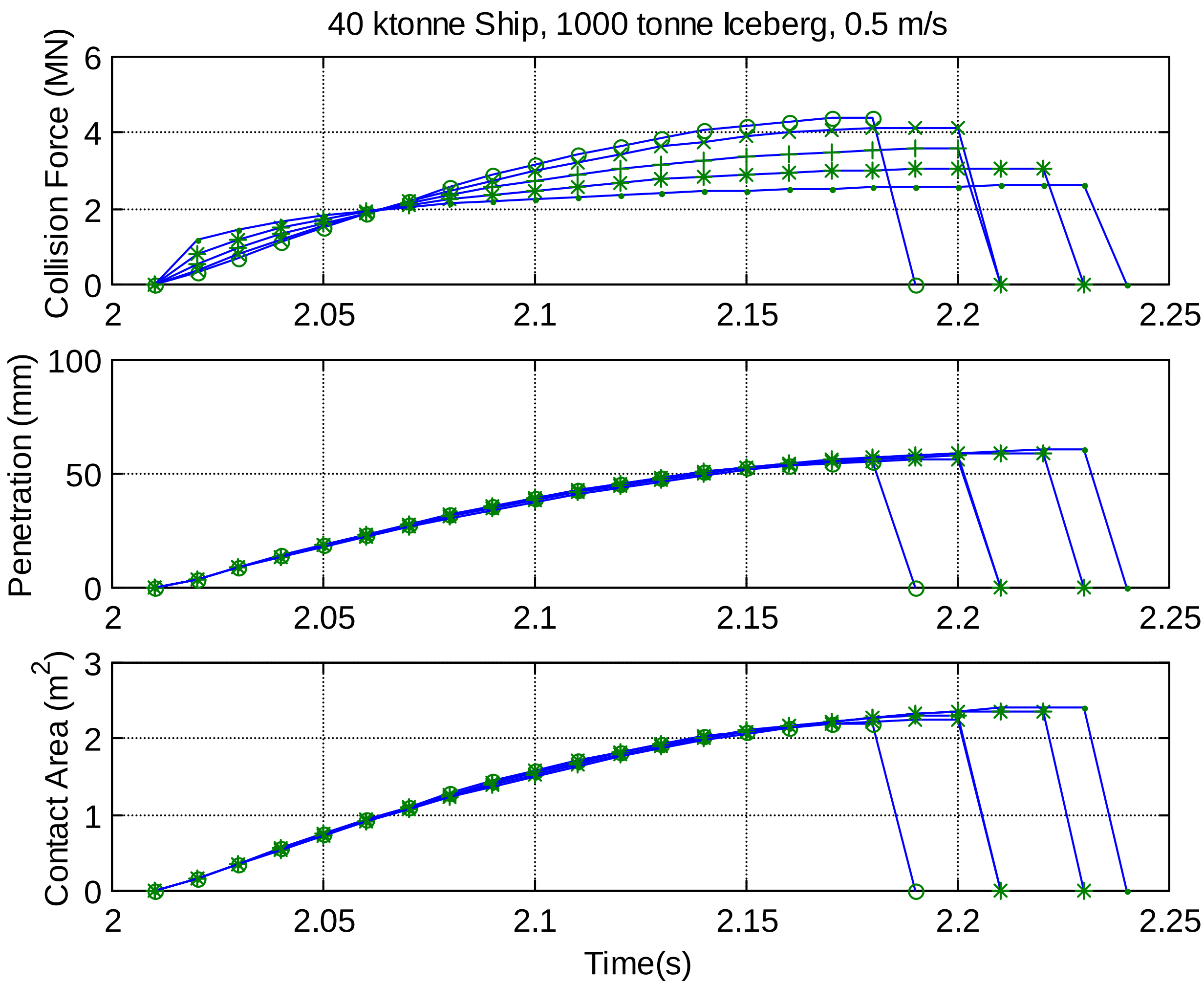
X	-0.1
+	-0.3
*	-0.5
•	-0.7



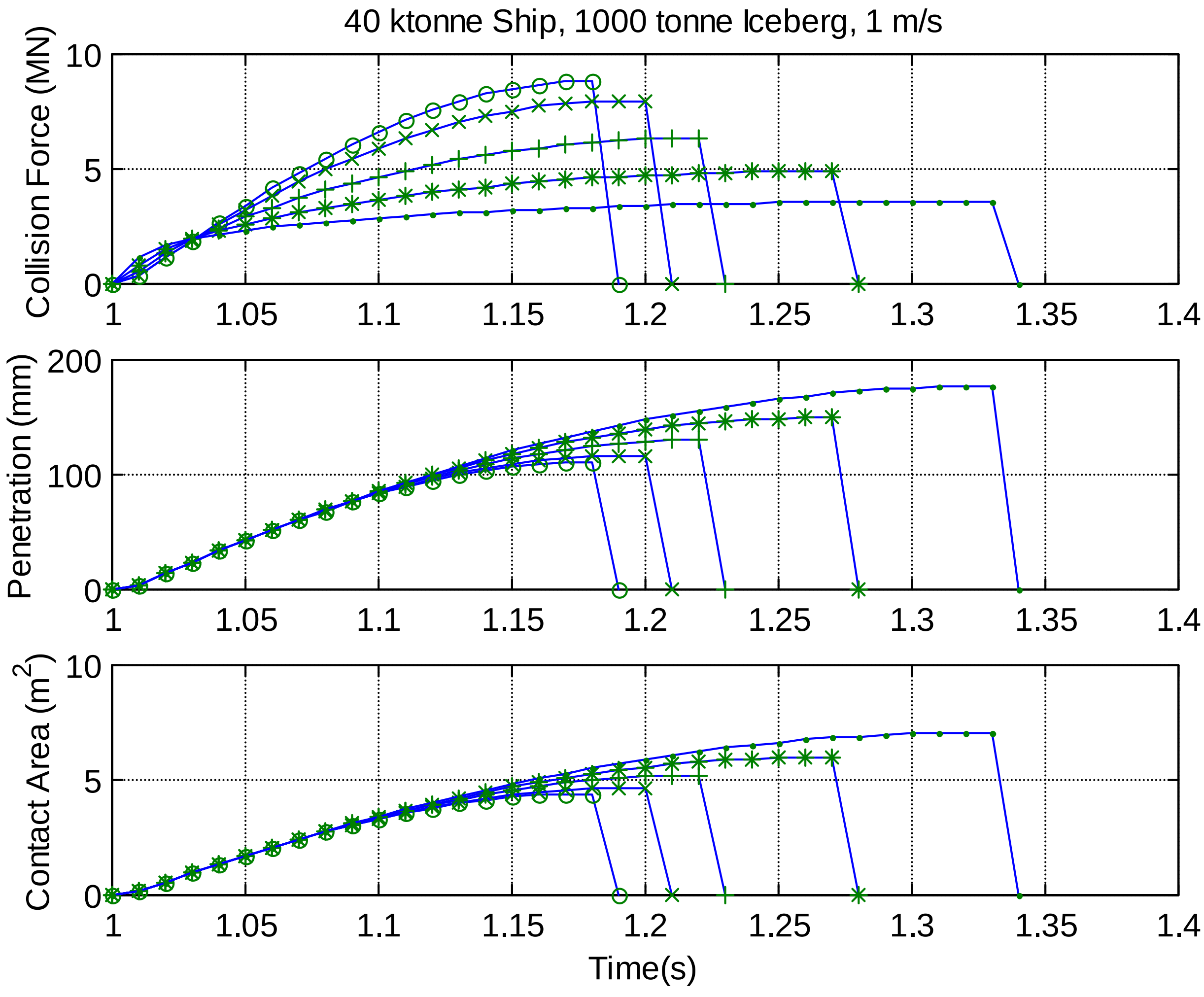
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



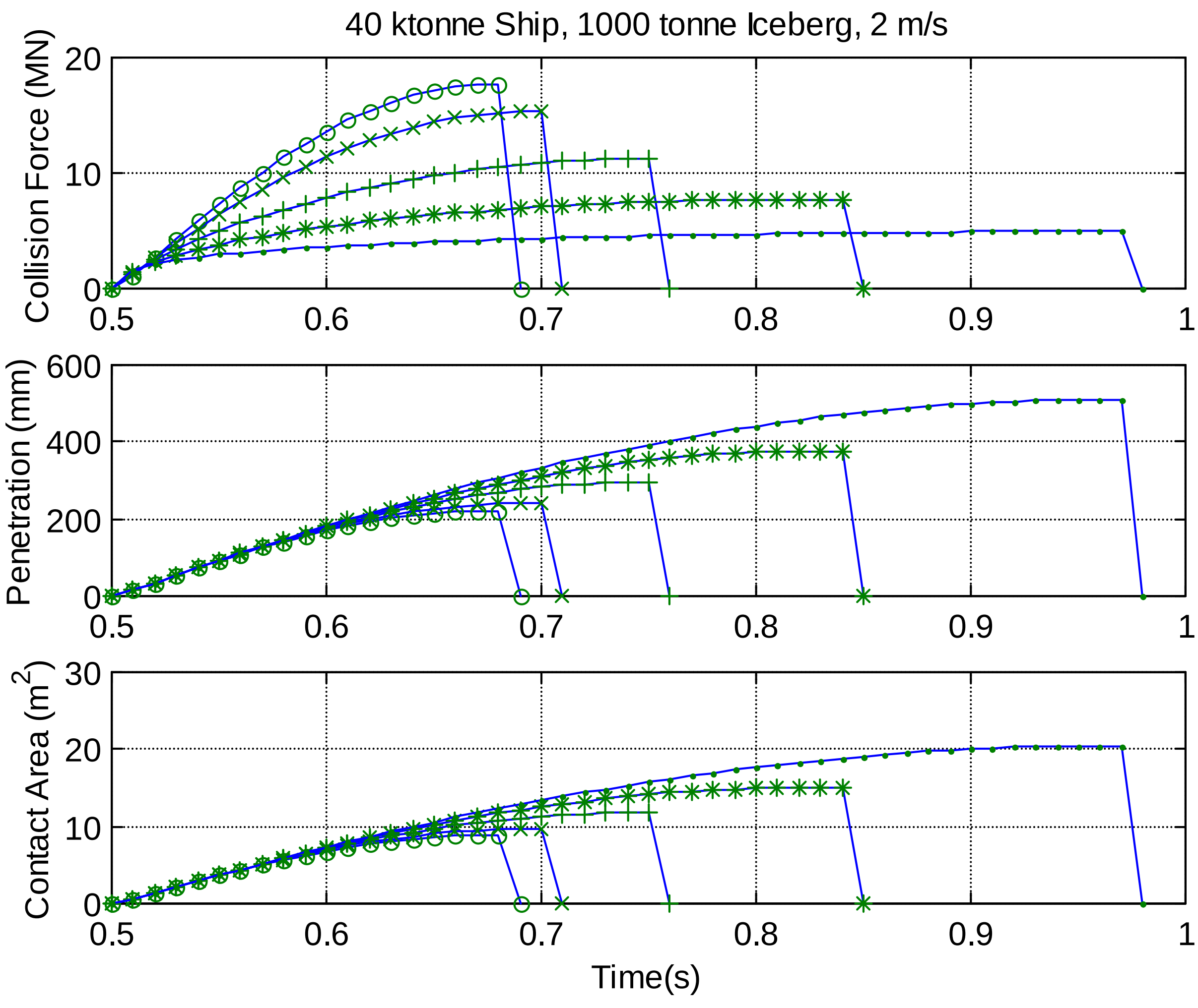
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



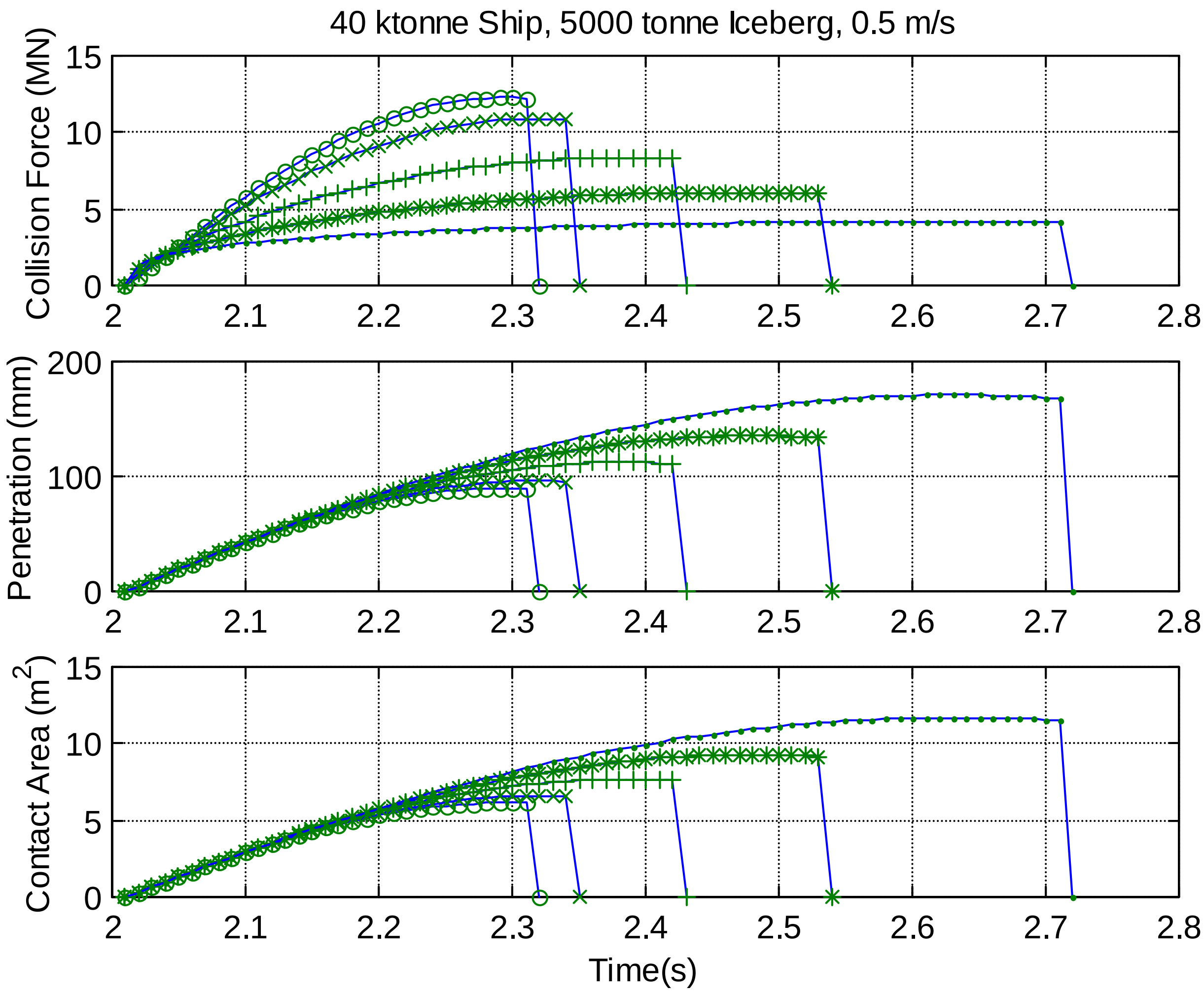
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



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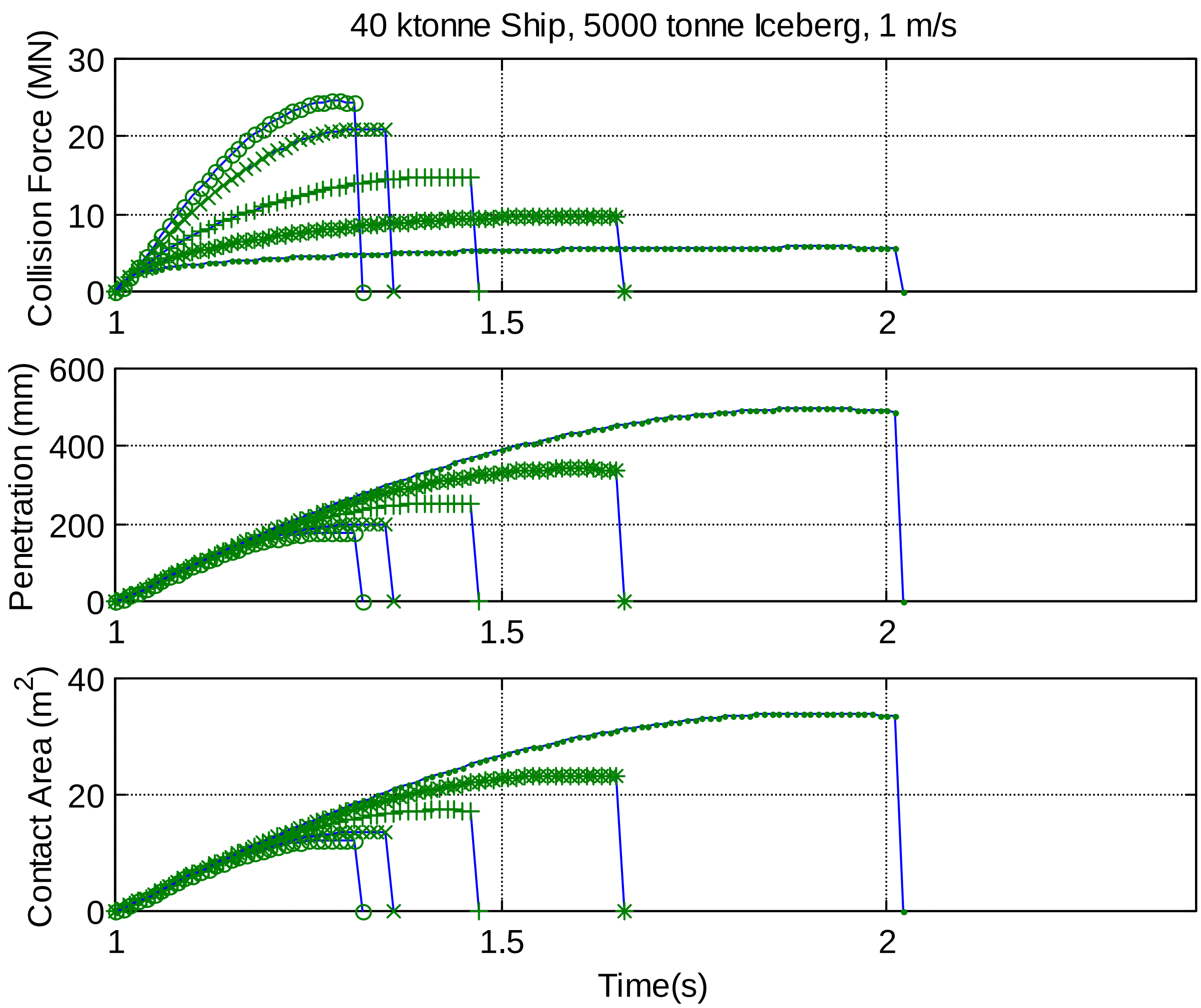
Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



Legend:

Symbol	Pressure Area Exponent
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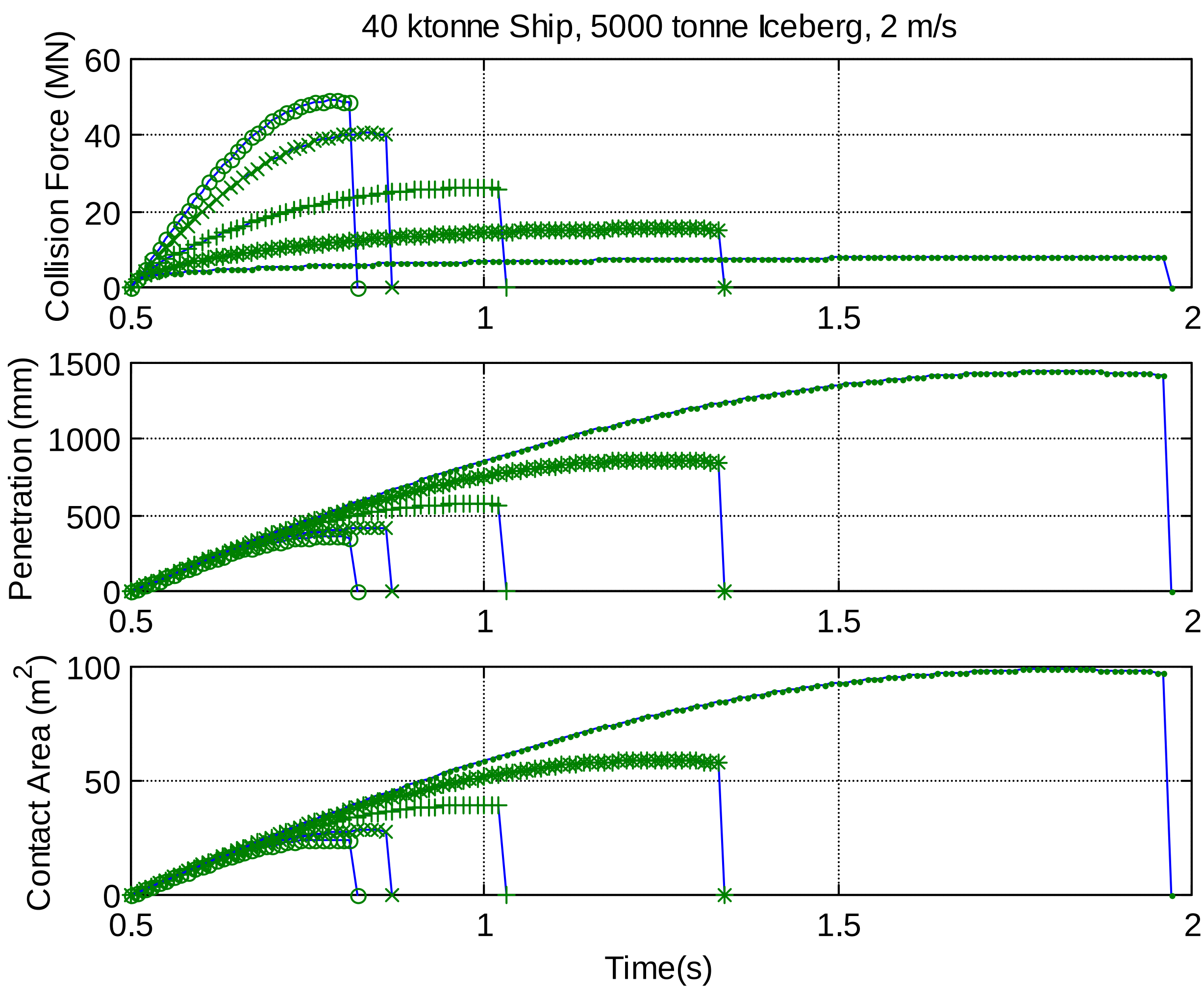
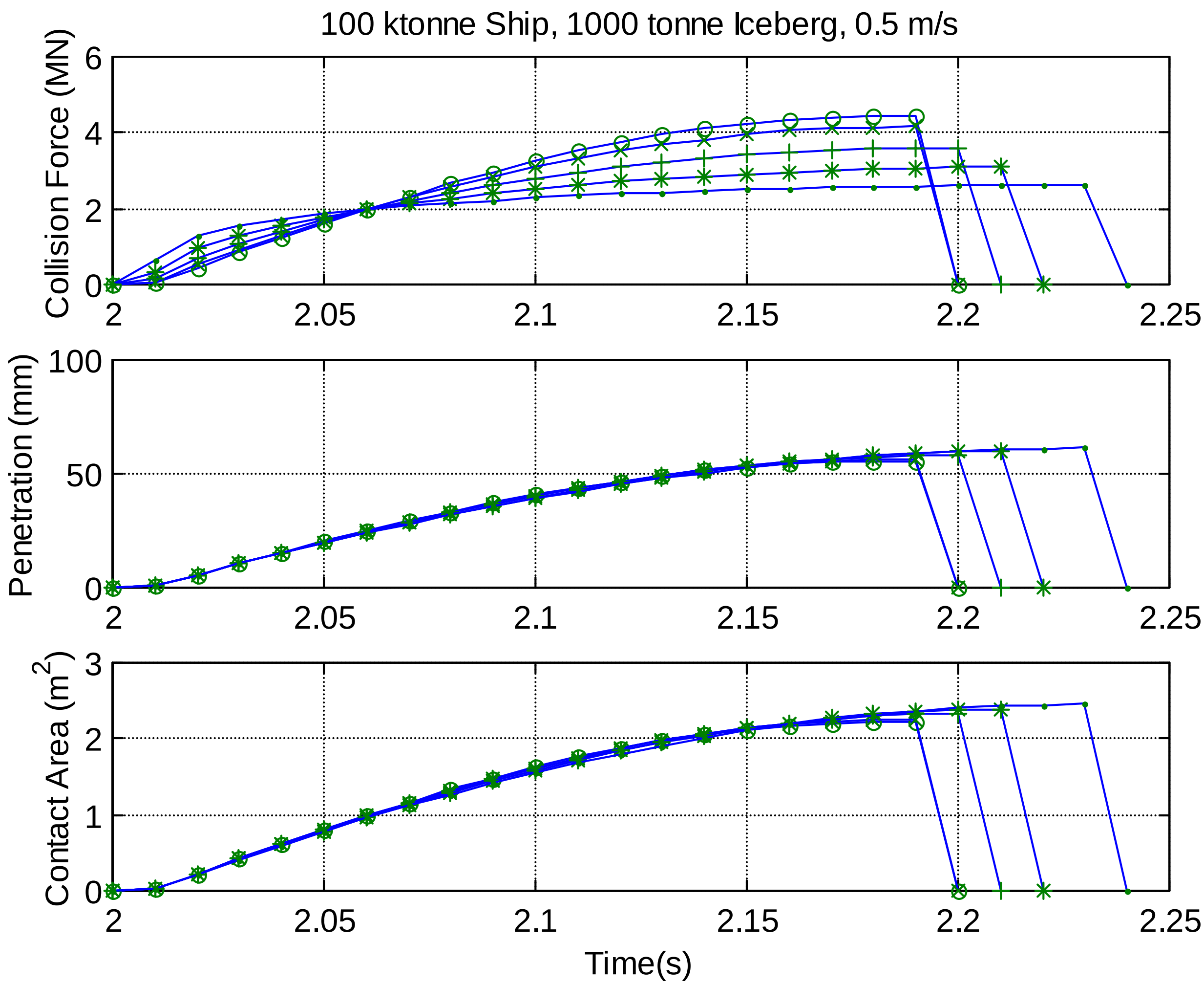
X	-0.1
+	-0.3
*	-0.5
•	-0.7



Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



Legend:

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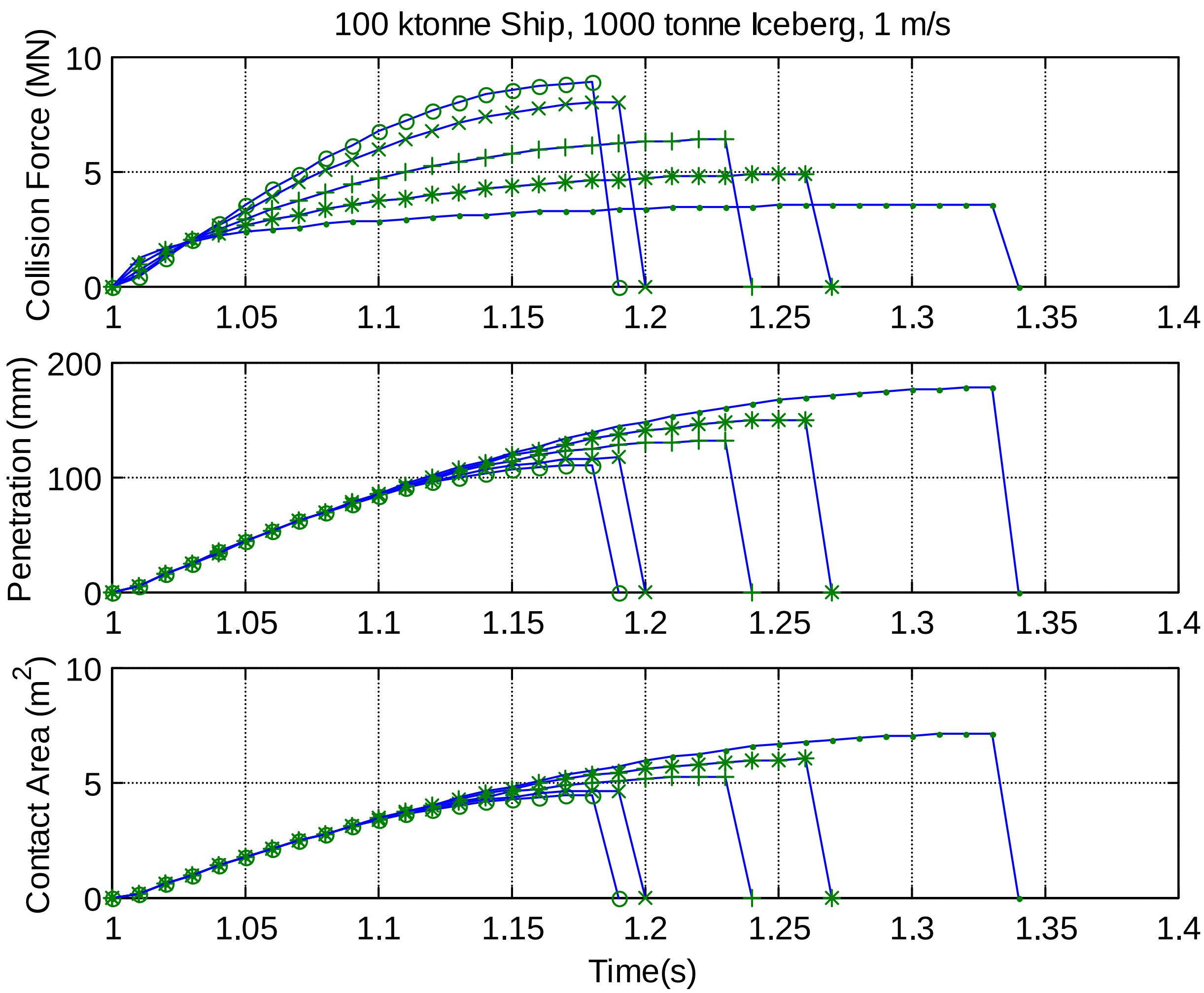
+	-0.3
*	-0.5
•	-0.7



Legend:

Symbol	Pressure Area Exponent
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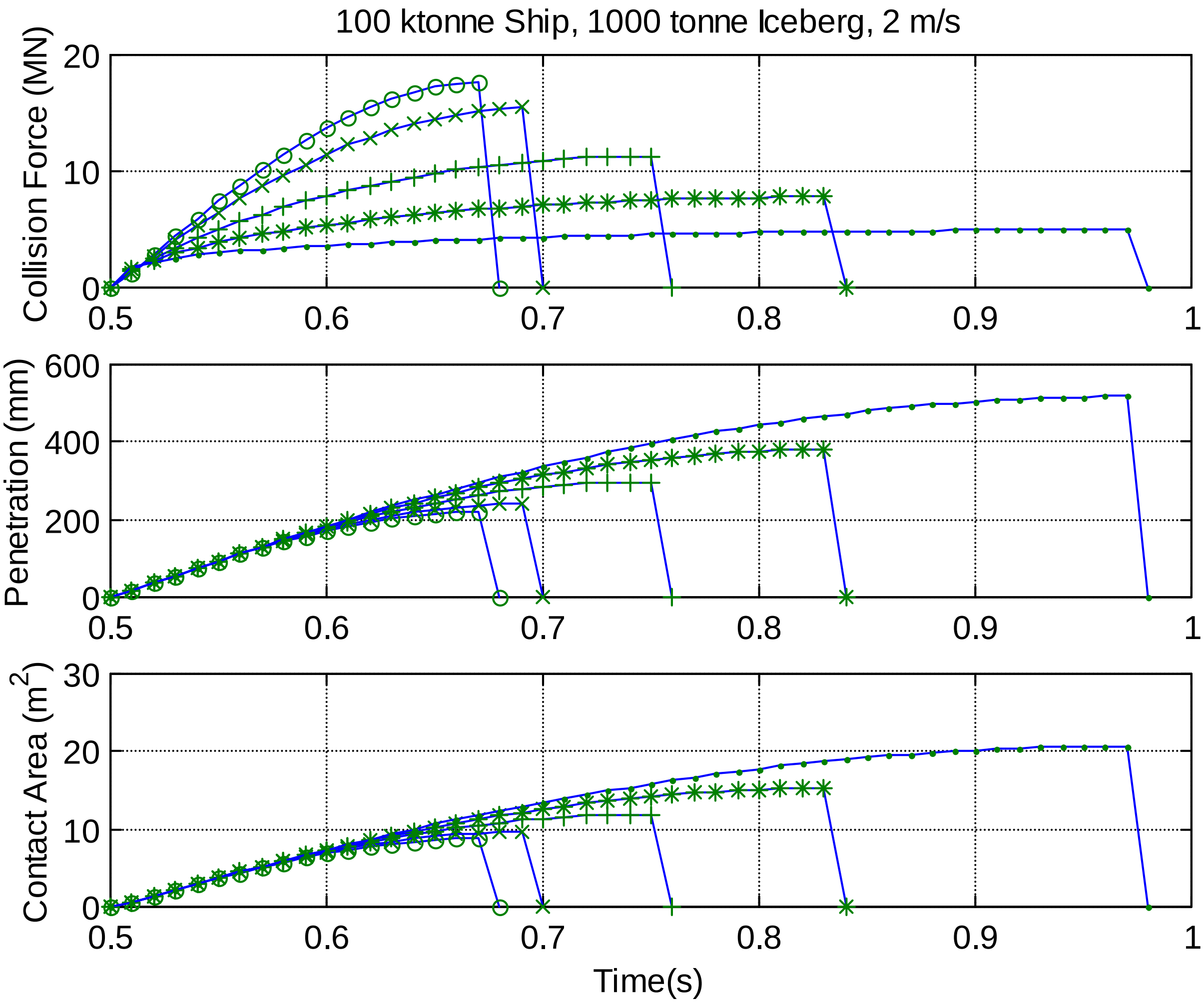
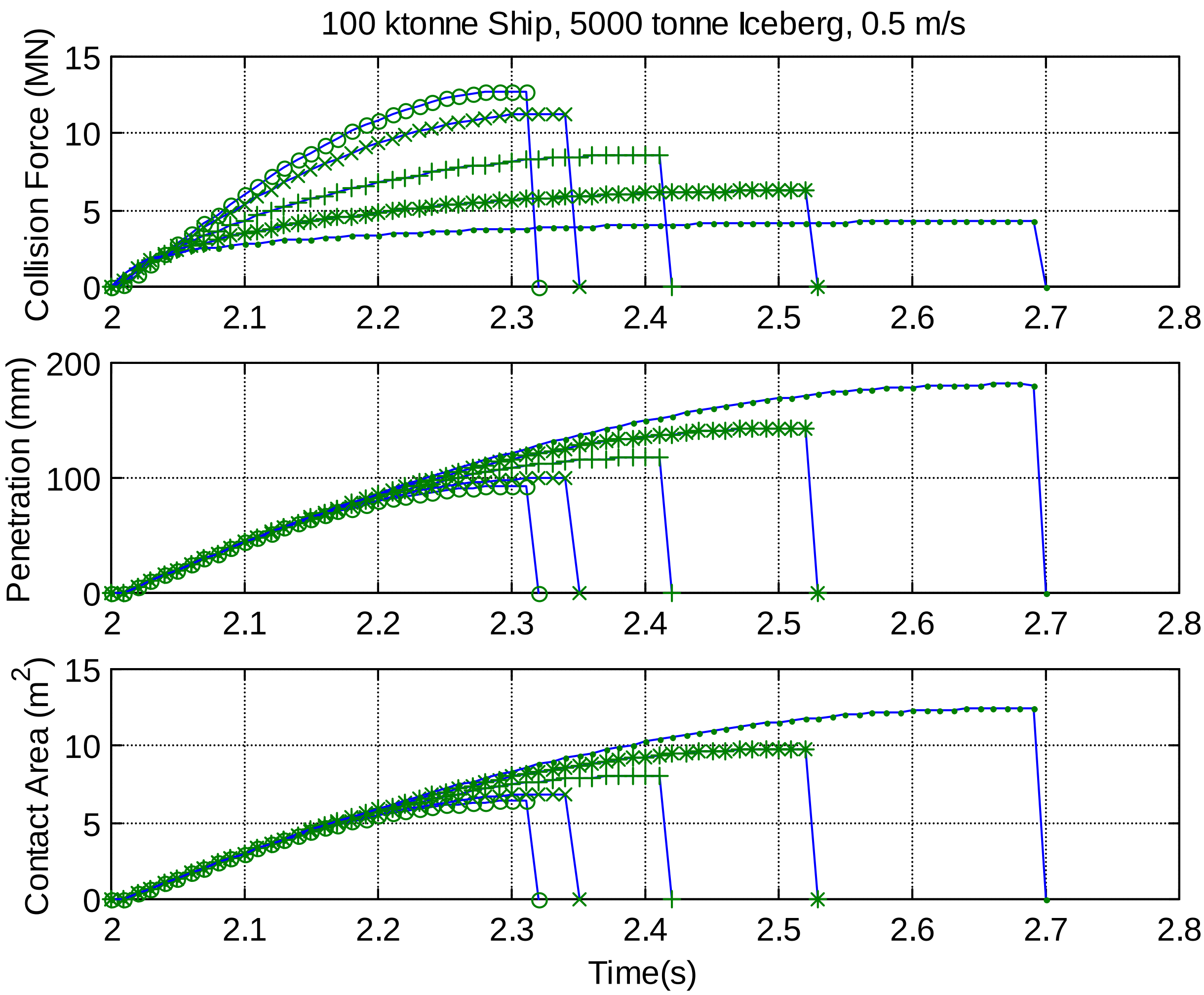
X	-0.1
+	-0.3
*	-0.5
•	-0.7



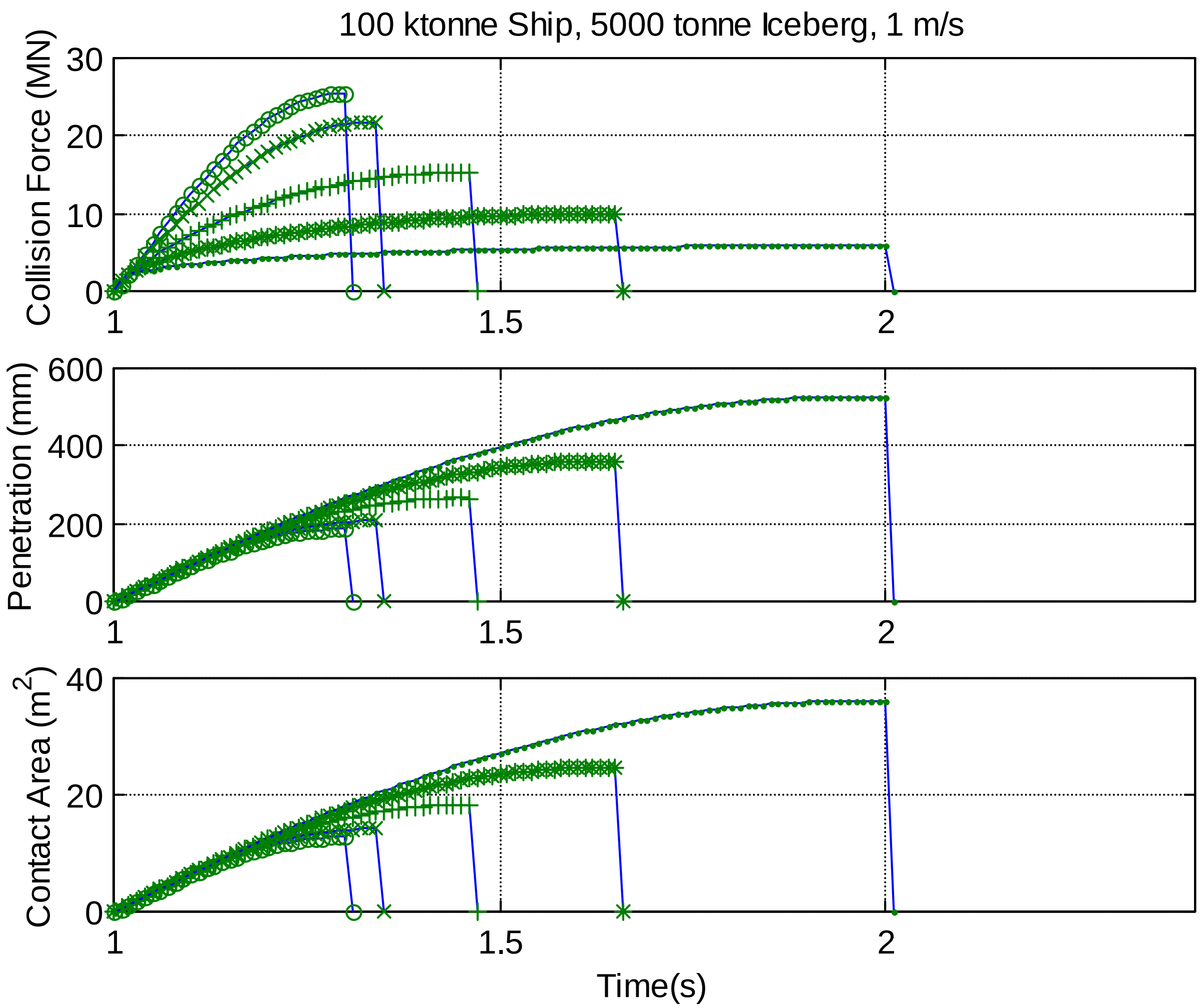
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



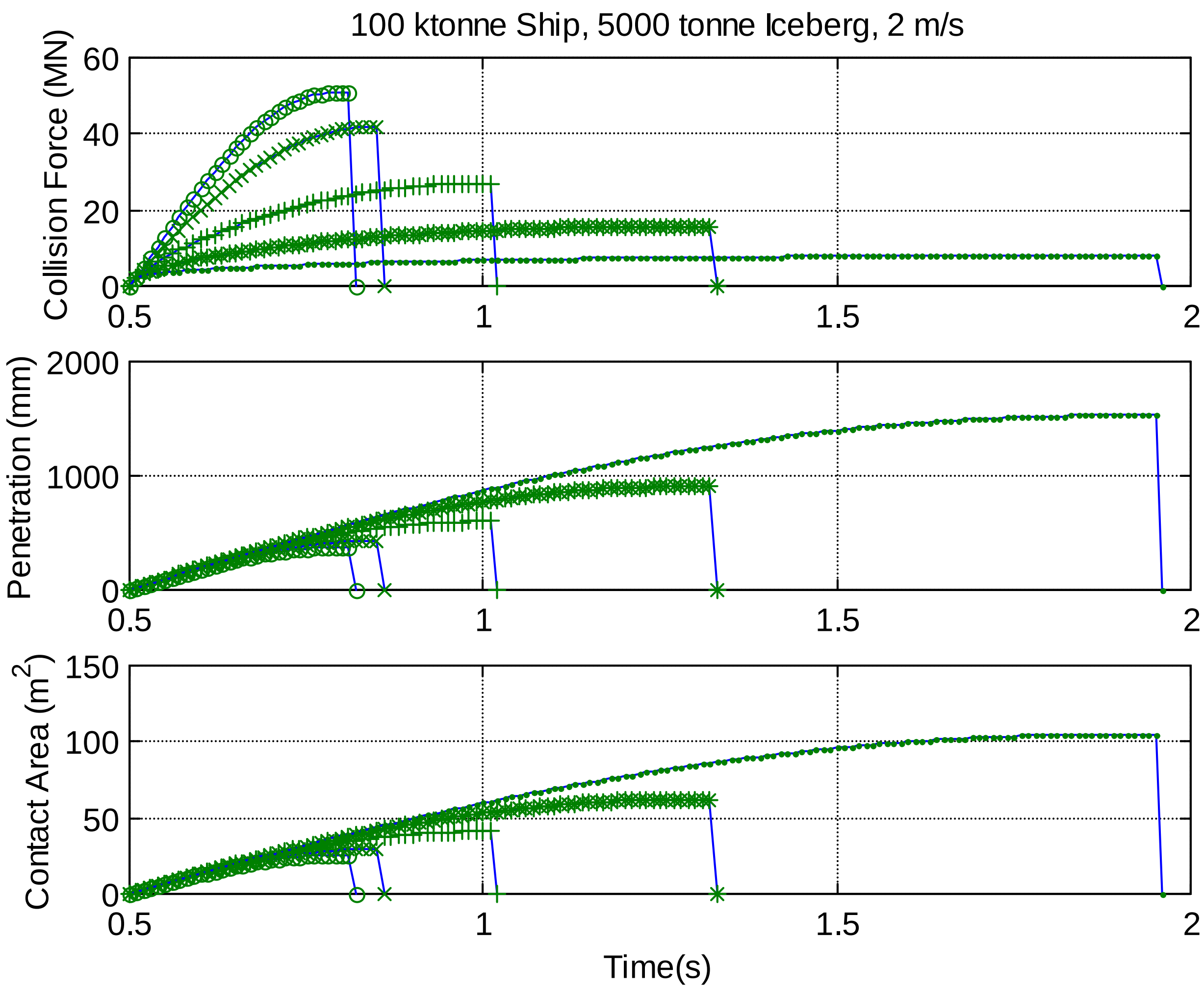
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



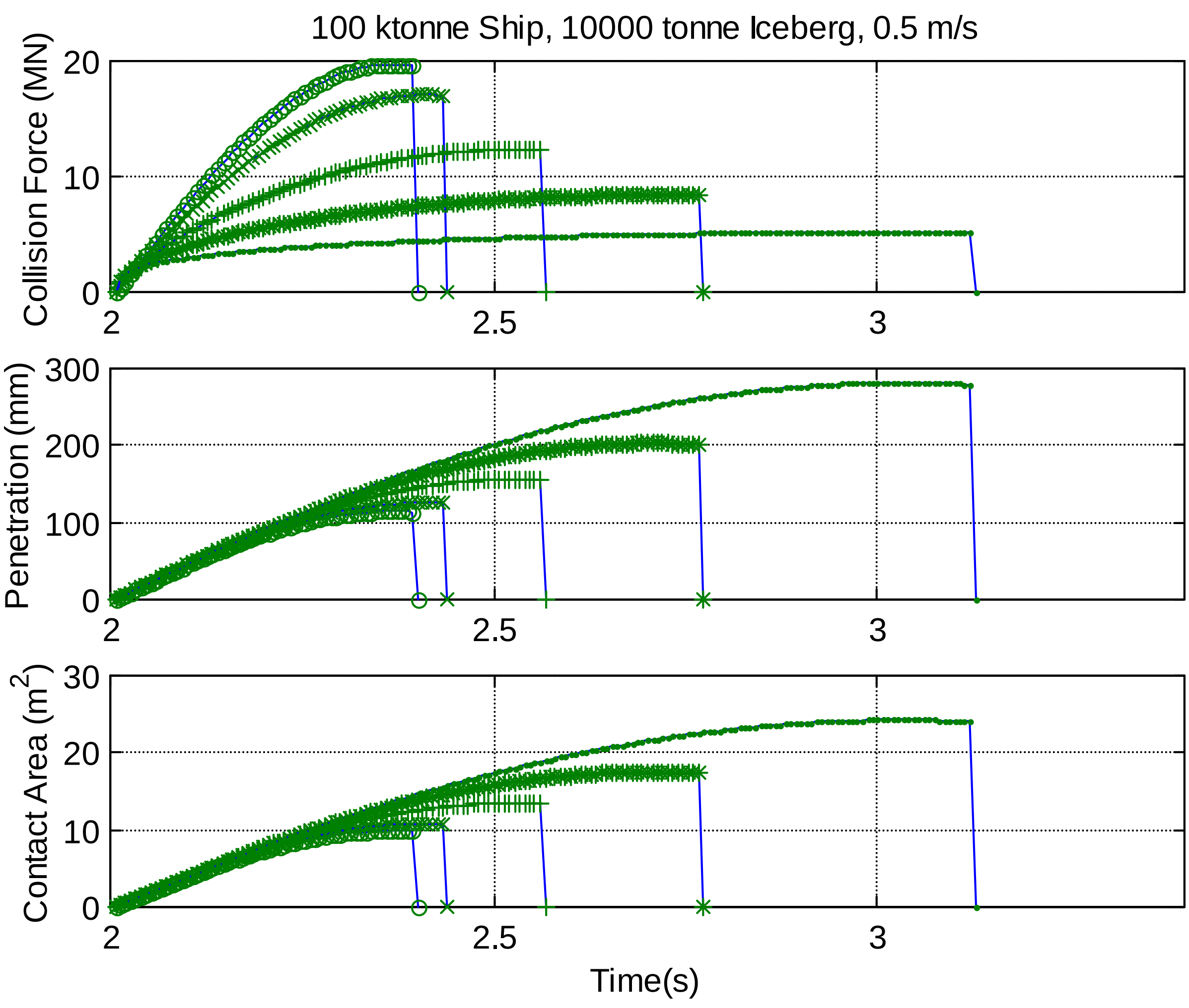
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



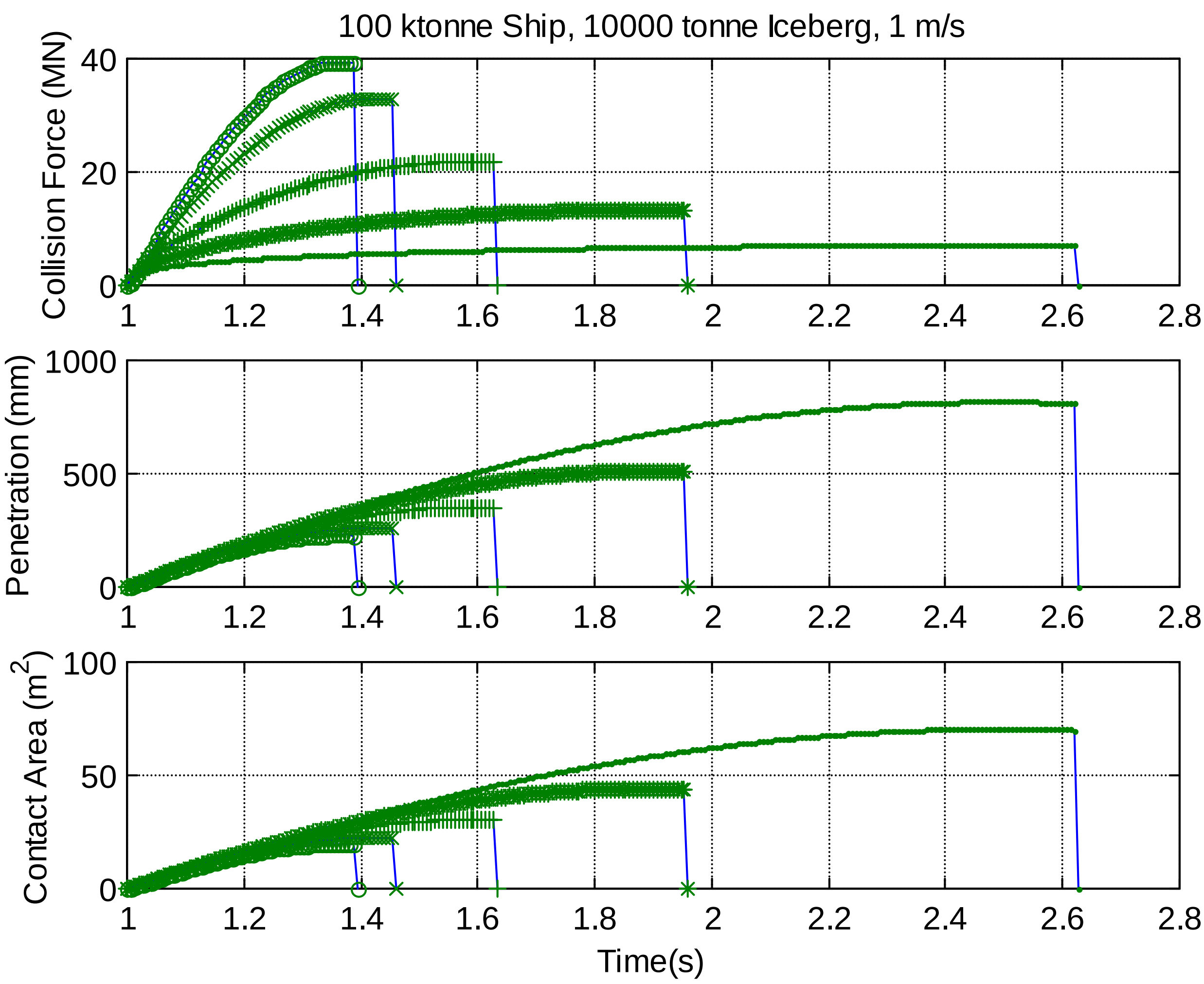
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



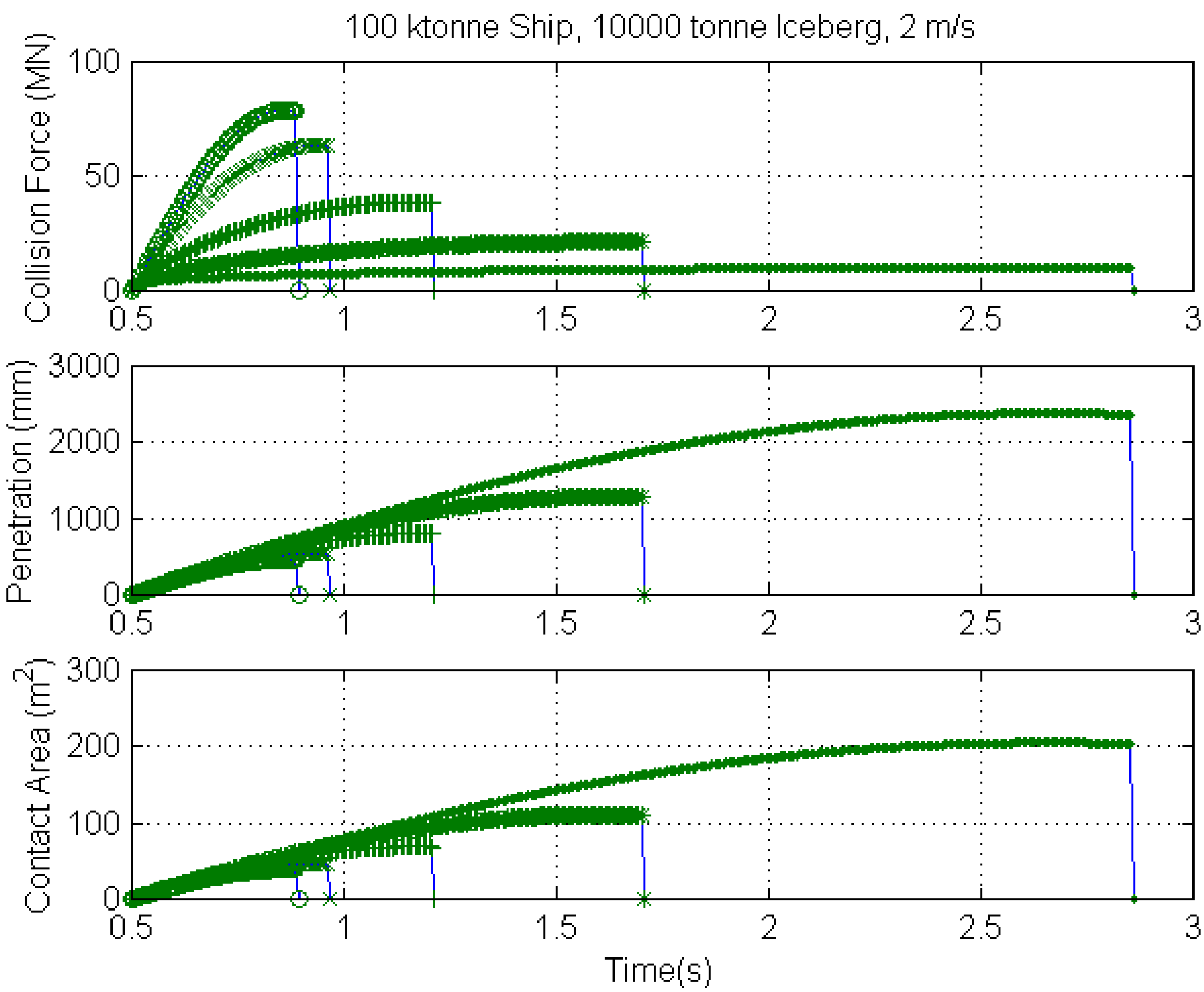
Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7



Legend:

Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7

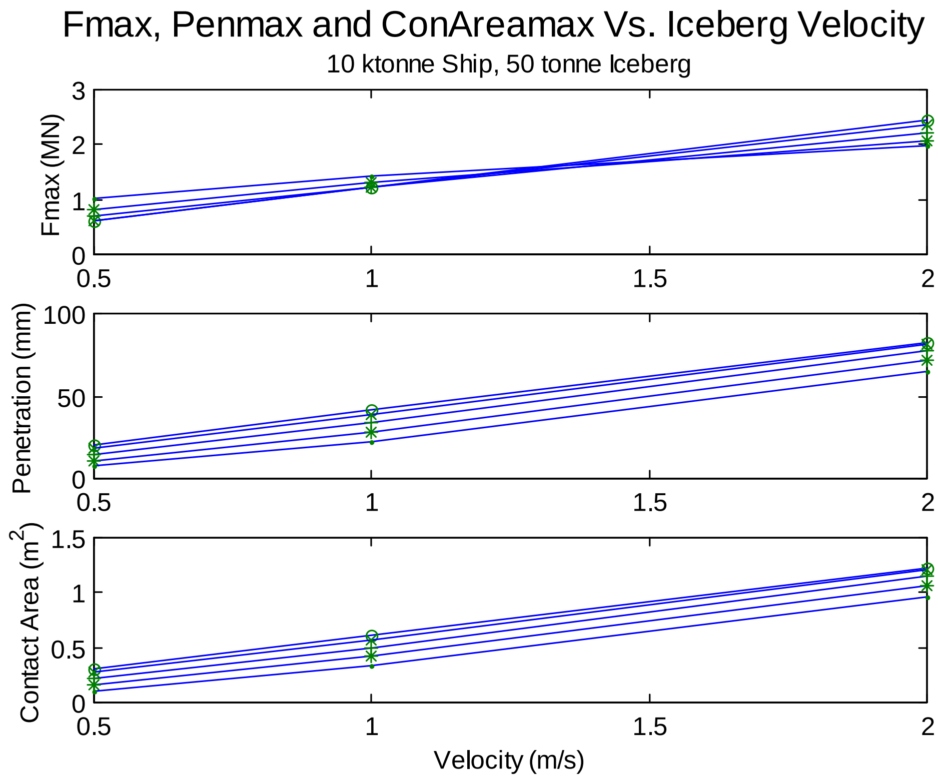


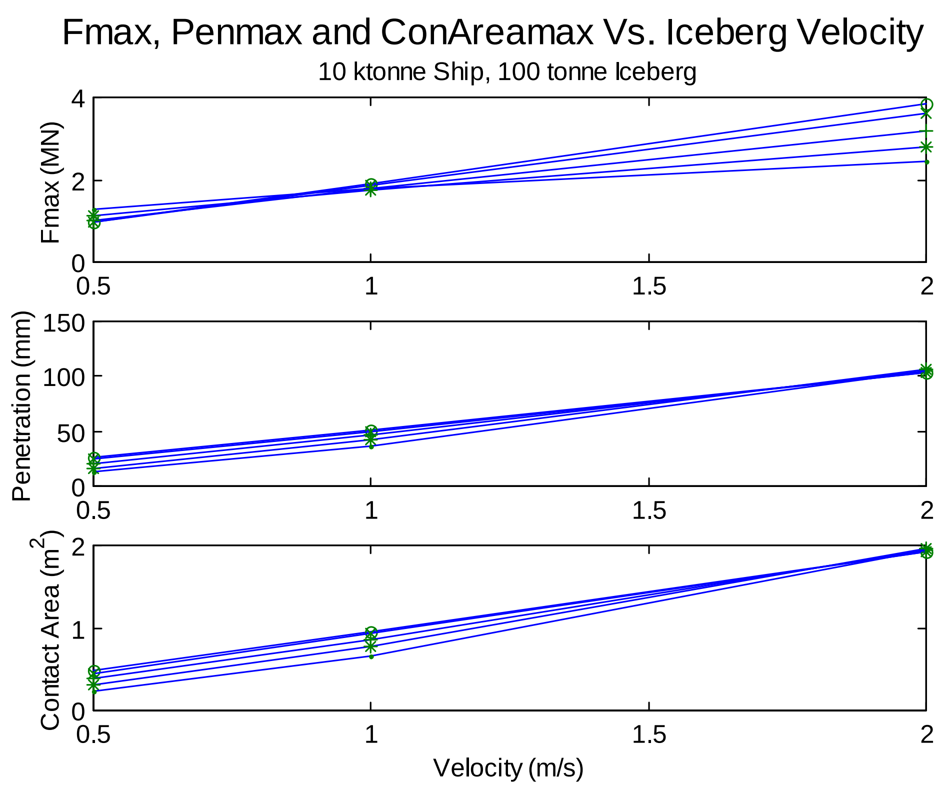
Appendix B:

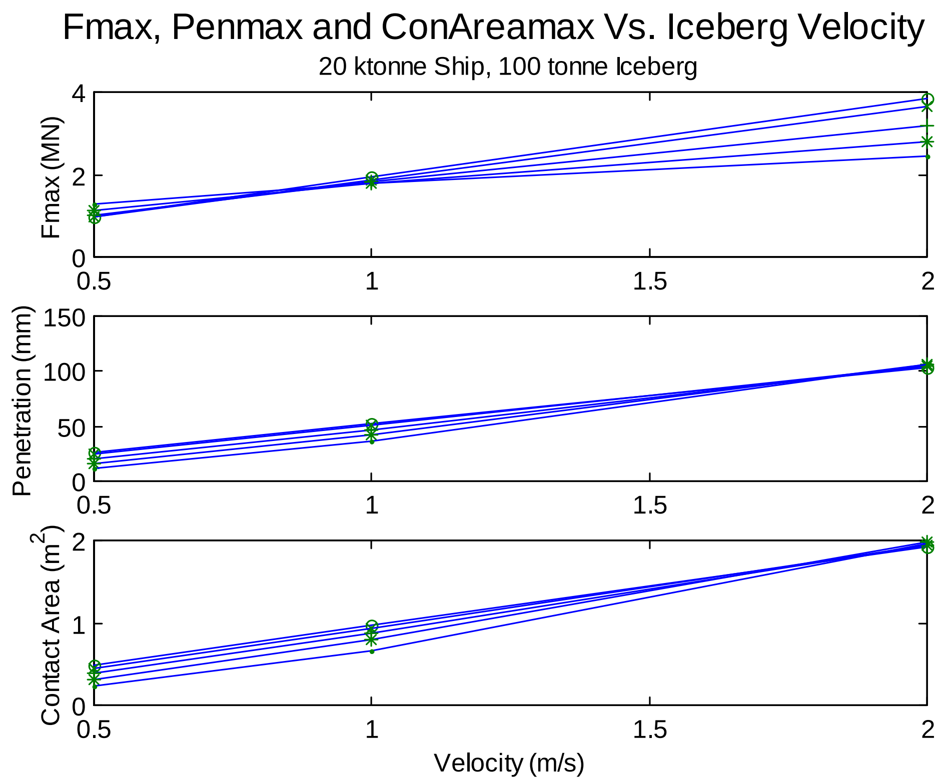
Plots of:
Fmax, Penmax and ConAreamax VS. **Ice Velocity**
for a family of **area exponent** curves
(ie. for all combinations of ship and ice displacements)

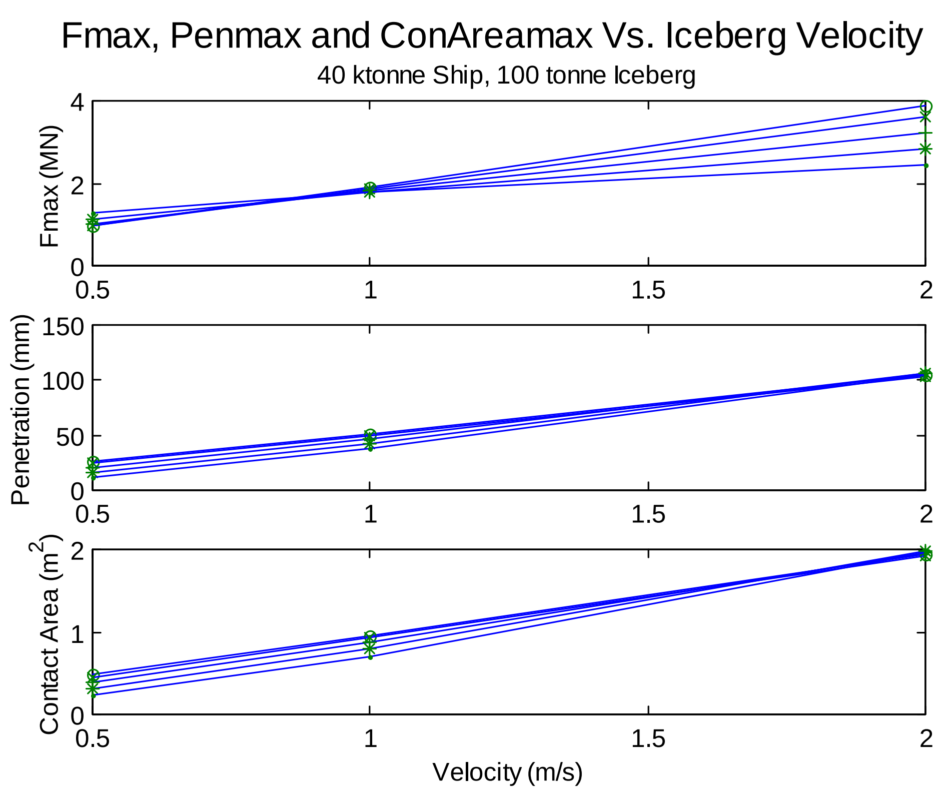
Legend:

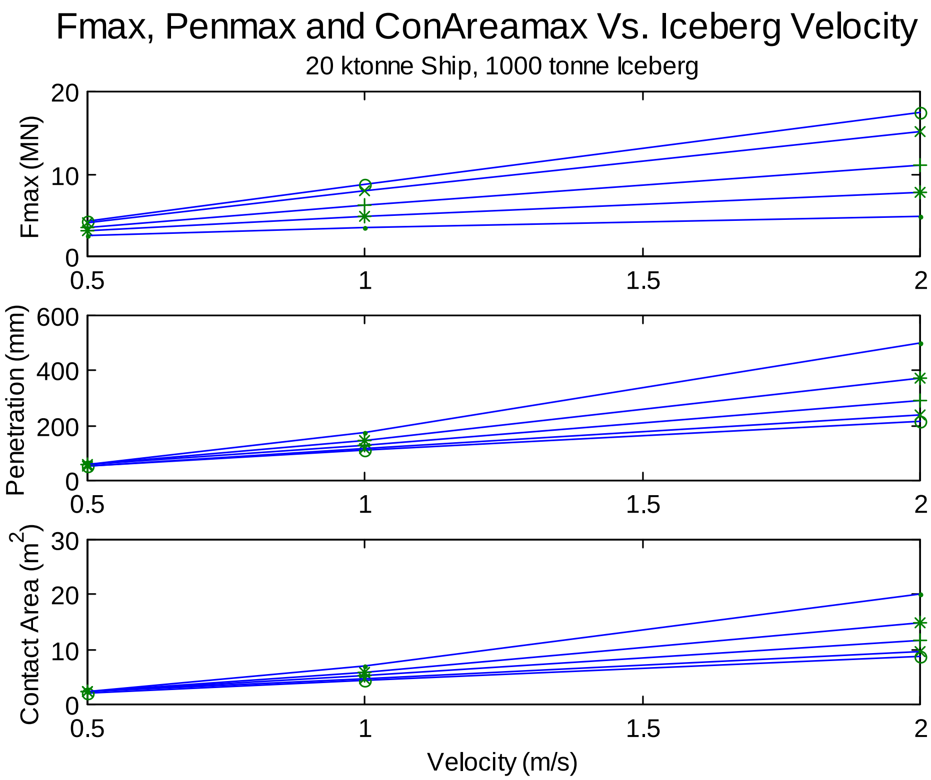
Symbol	Pressure Area Exponent
O	0.0
X	-0.1
+	-0.3
*	-0.5
•	-0.7

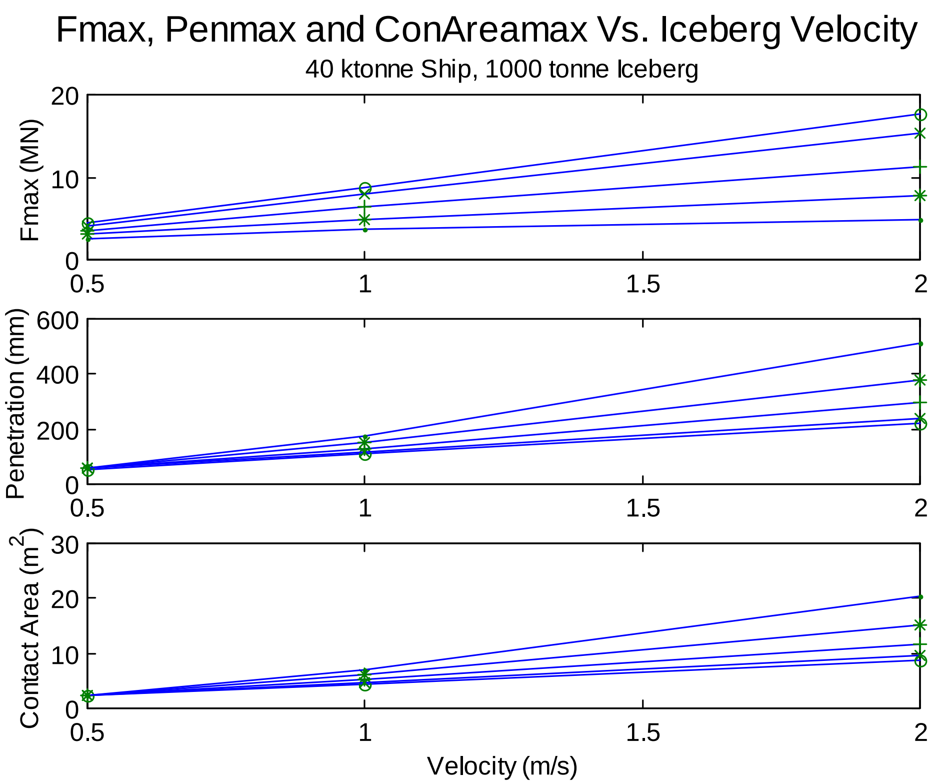

Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
10 ktonne Ship, 50 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Velocity (m/s)

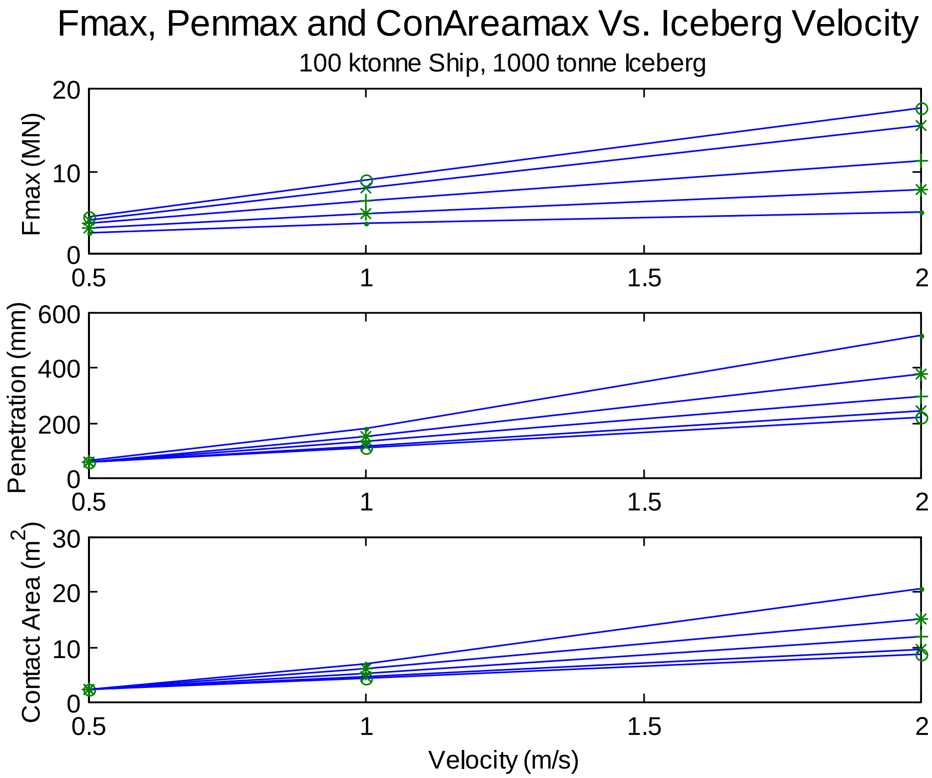

Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
10 ktonne Ship, 100 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Velocity (m/s)

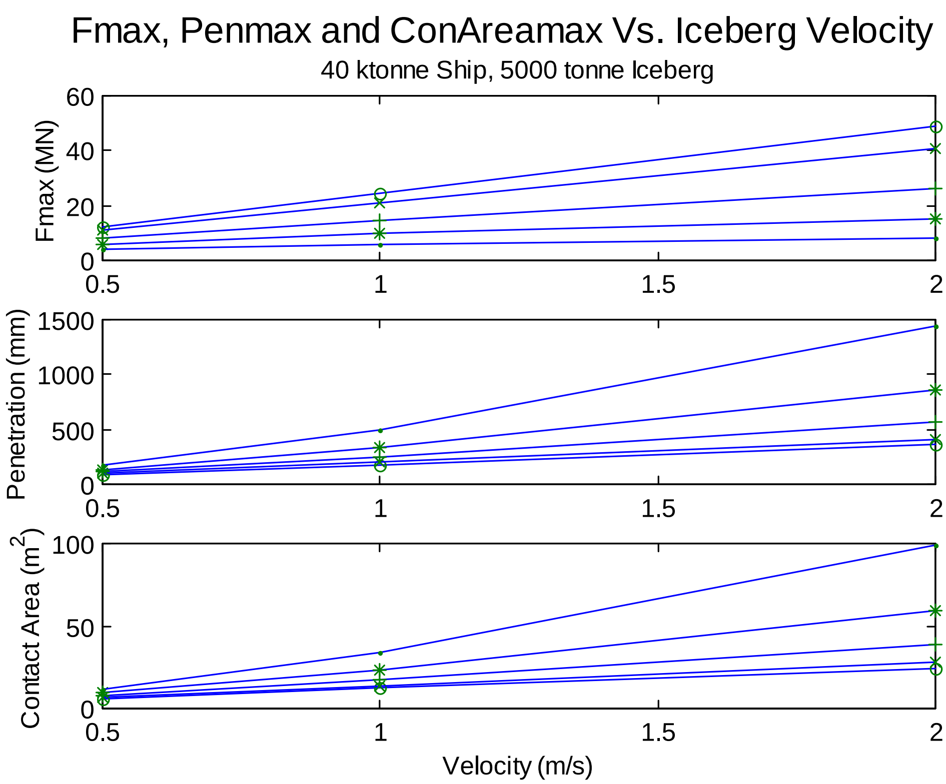

Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
20 ktonne Ship, 100 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Velocity (m/s)
0.5
1
1.5
2

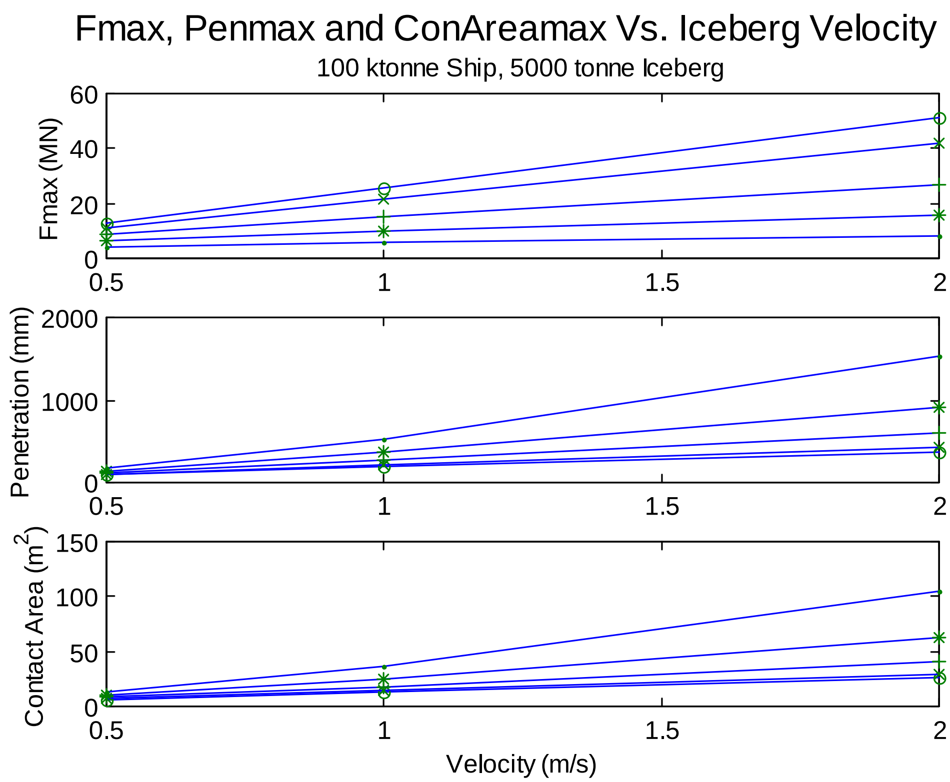

Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
40 ktonne Ship, 100 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Velocity (m/s)
0.5
1
1.5
2

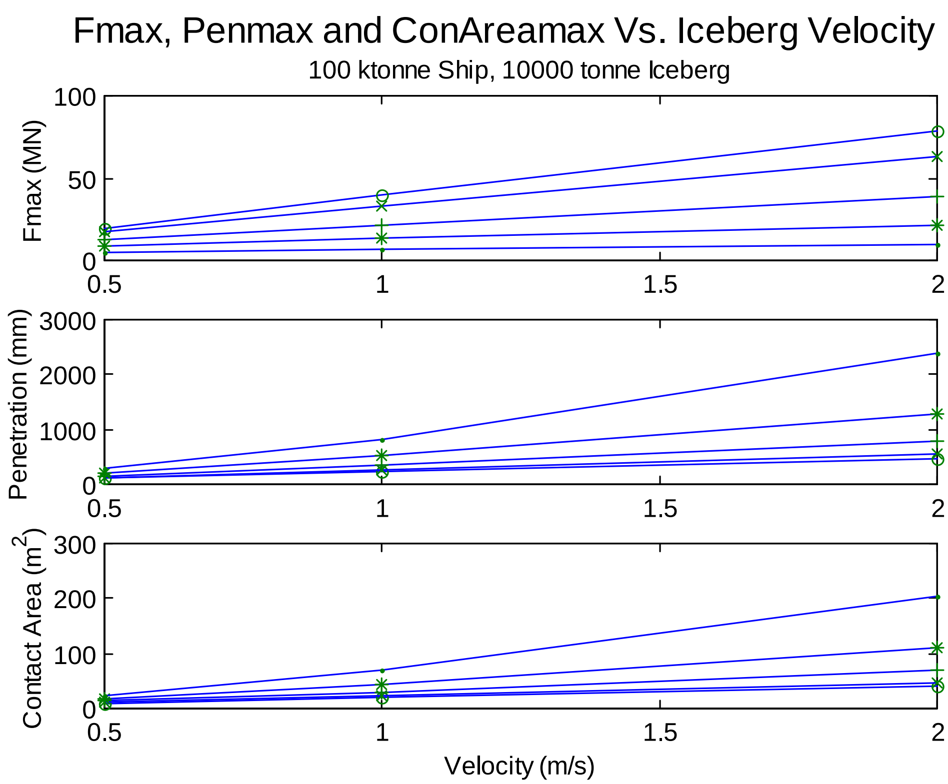

Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
20 ktonne Ship, 1000 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m^2)
Velocity (m/s)


Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
40 ktonne Ship, 1000 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m^2)
Velocity (m/s)


Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
100 ktonne Ship, 1000 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Velocity (m/s)


Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
40 ktonne Ship, 5000 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Velocity (m/s)


Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
100 ktonne Ship, 5000 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Velocity (m/s)
0.5
1
1.5
2
60
40
20
0
2000
1000
150
100
50

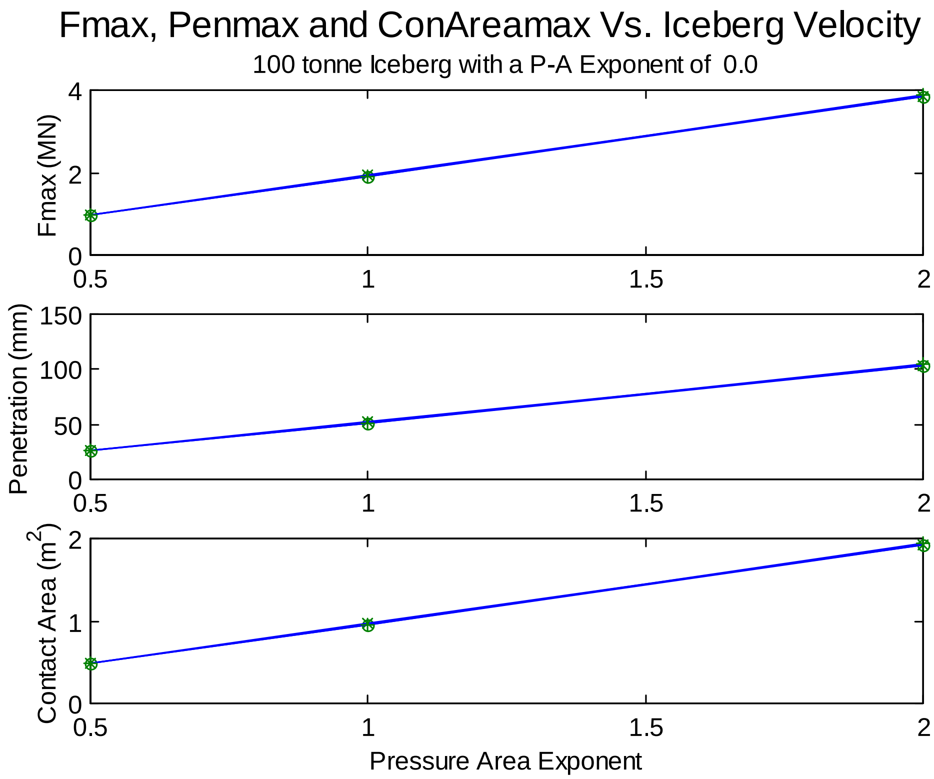

Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
100 ktonne Ship, 10000 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Velocity (m/s)
0.5
1
1.5
2
100
50
0
3000
2000
1000
300
200

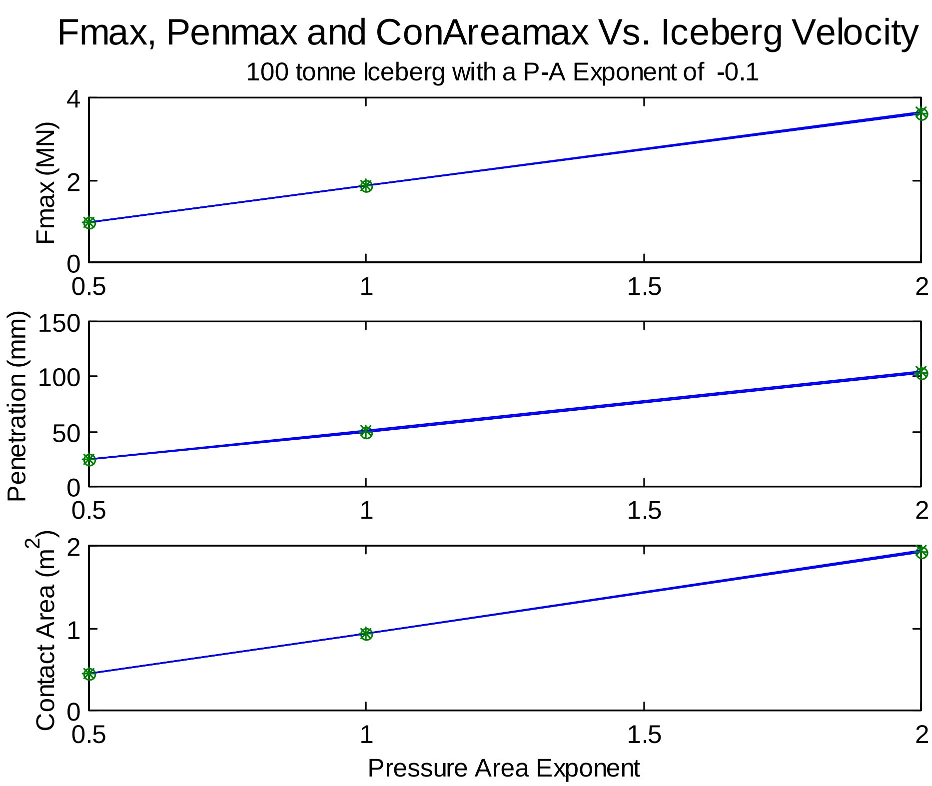
Appendix C:

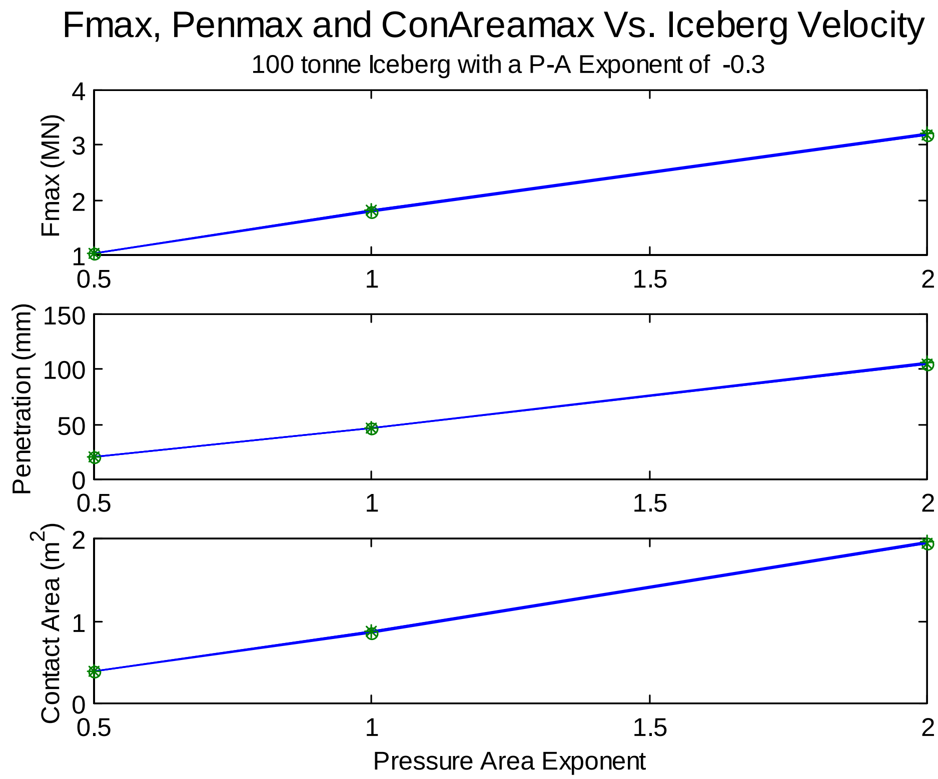
Plots of
Fmax, Penmax and ConAreamax VS. **Ice Velocity**
for a family of **ship displacement** curves
(ie. for all combinations of ice displacements and area exponents)

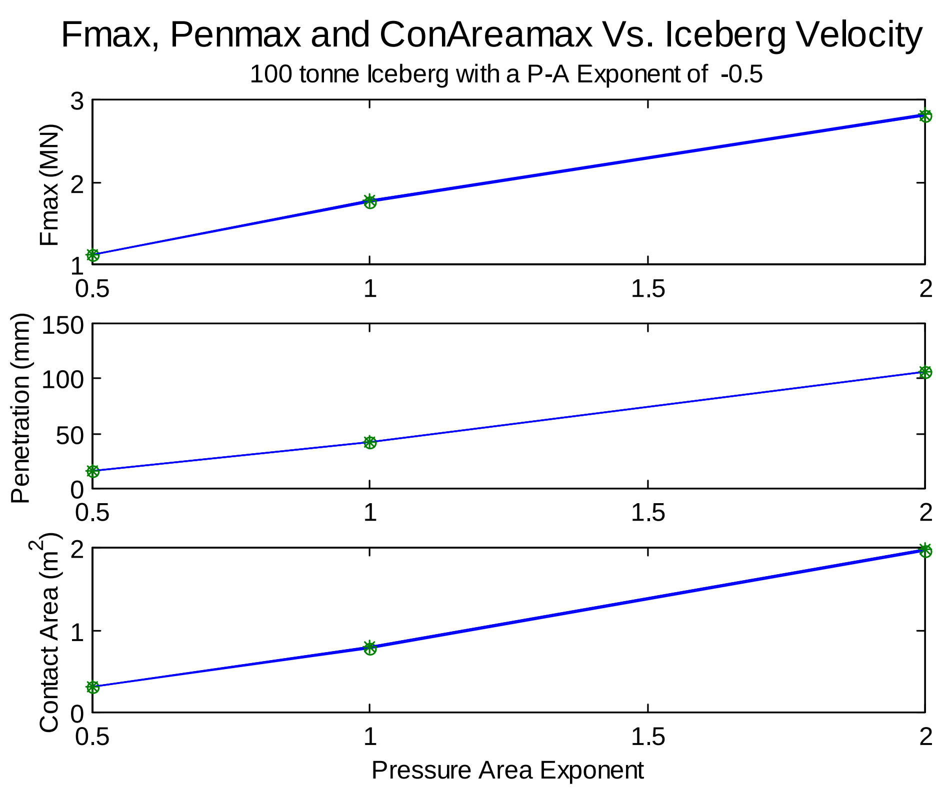
Legend:

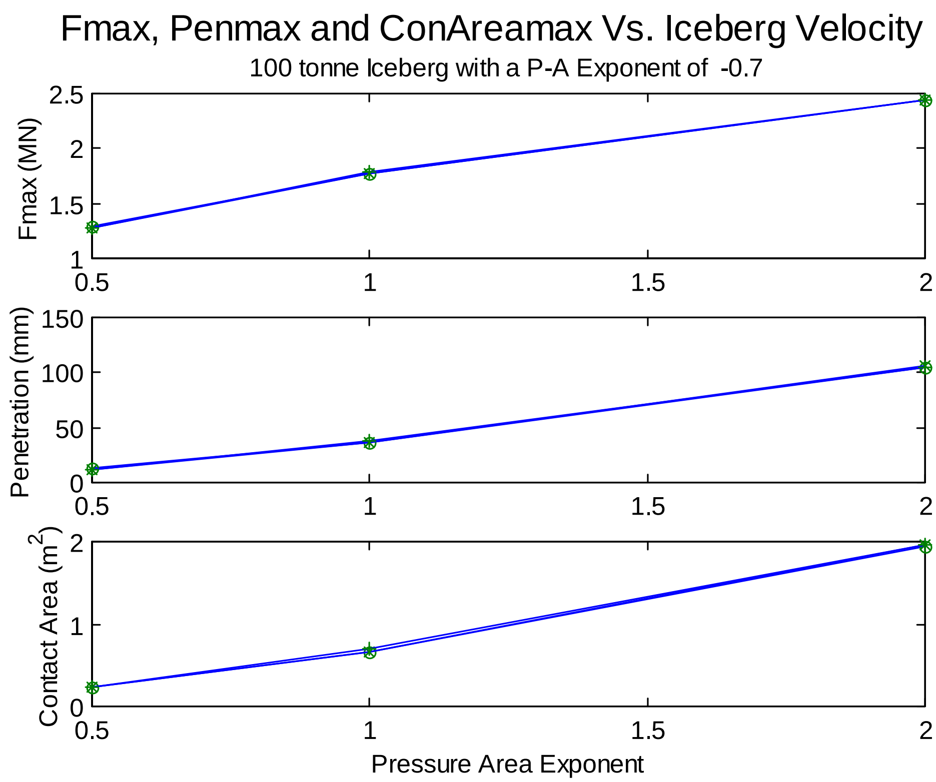
Symbol	Ship Displacement (kt)
O	10
X	20
+	40
*	100

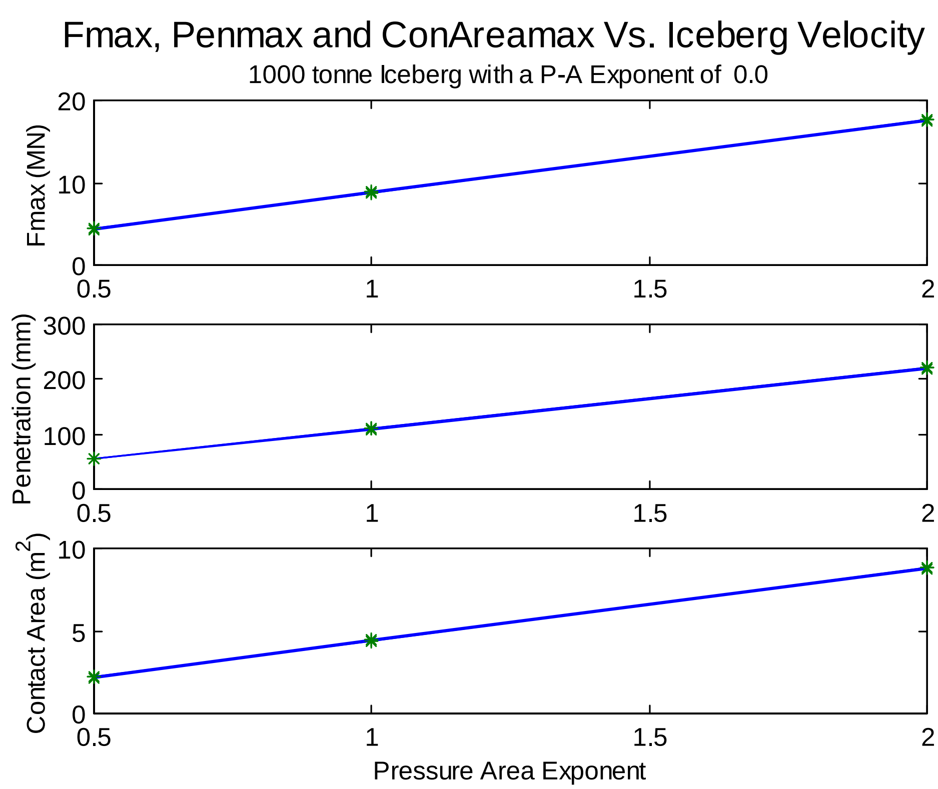

Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
100 tonne Iceberg with a P-A Exponent of 0.0
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent

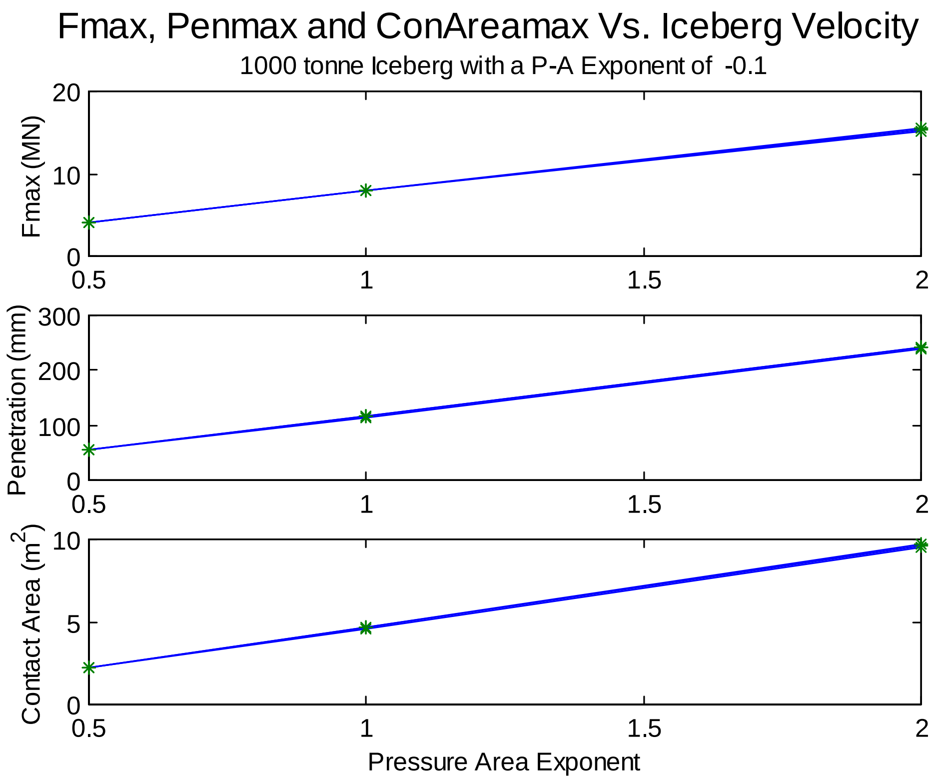

Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
100 tonne Iceberg with a P-A Exponent of -0.1
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent

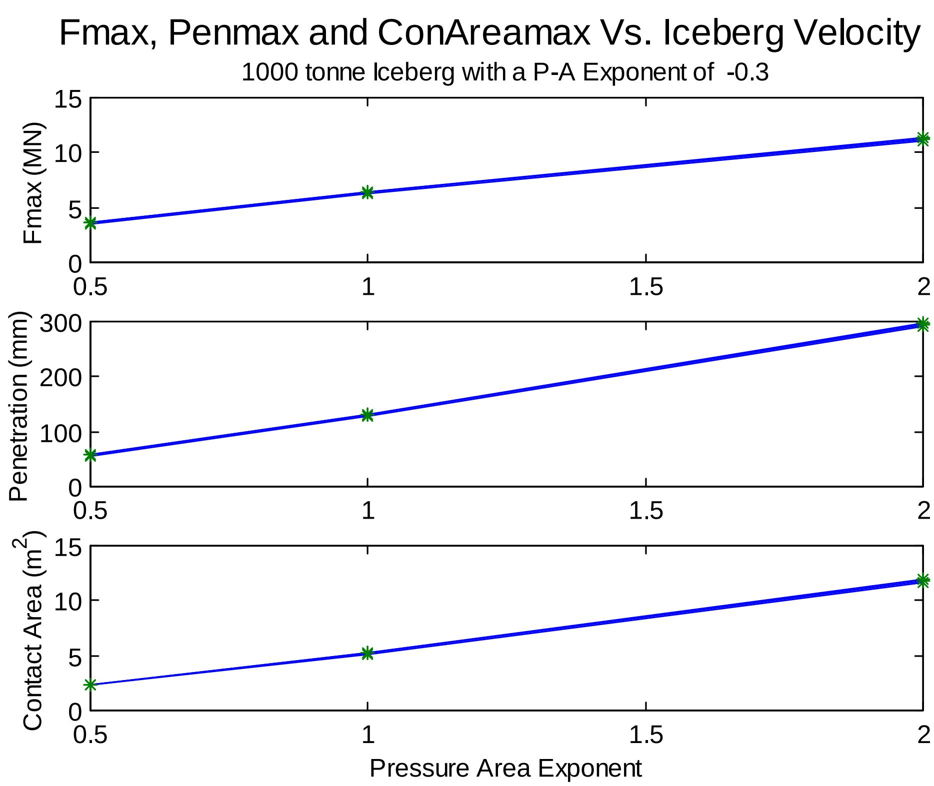

Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
100 tonne Iceberg with a P-A Exponent of -0.3
Fmax (MN)
Penetration (mm)
Contact Area (m^2)
Pressure Area Exponent

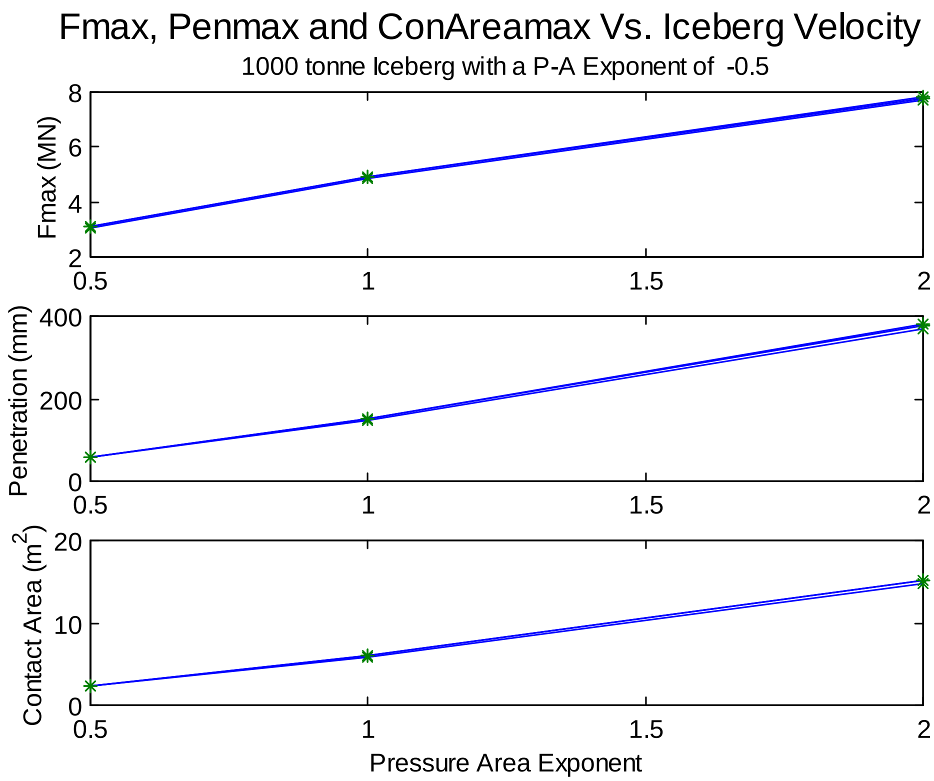

Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
100 tonne Iceberg with a P-A Exponent of -0.5
Fmax (MN)
Penetration (mm)
Contact Area (m^2)
Pressure Area Exponent

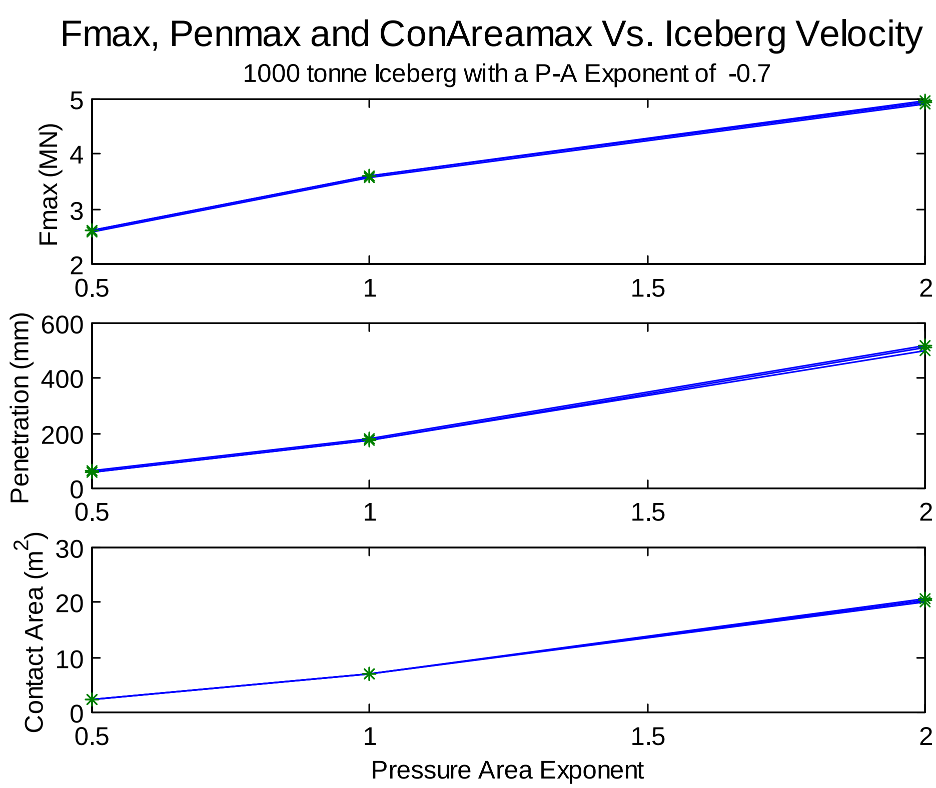

Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
100 tonne Iceberg with a P-A Exponent of -0.7
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent


Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
1000 tonne Iceberg with a P-A Exponent of 0.0
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent


Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
1000 tonne Iceberg with a P-A Exponent of -0.1
Fmax (MN)
Penetration (mm)
Contact Area (m^2)
Pressure Area Exponent
0
10
20
0
100
200
300
0
5
10
0.5
1
1.5
2


Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
1000 tonne Iceberg with a P-A Exponent of -0.3
Fmax (MN)
Penetration (mm)
Contact Area (m^2)
Pressure Area Exponent
0
5
10
15
0
100
200
300
0.5
1
1.5
2


Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
1000 tonne Iceberg with a P-A Exponent of -0.5
Fmax (MN)
Penetration (mm)
Contact Area (m^2)
Pressure Area Exponent

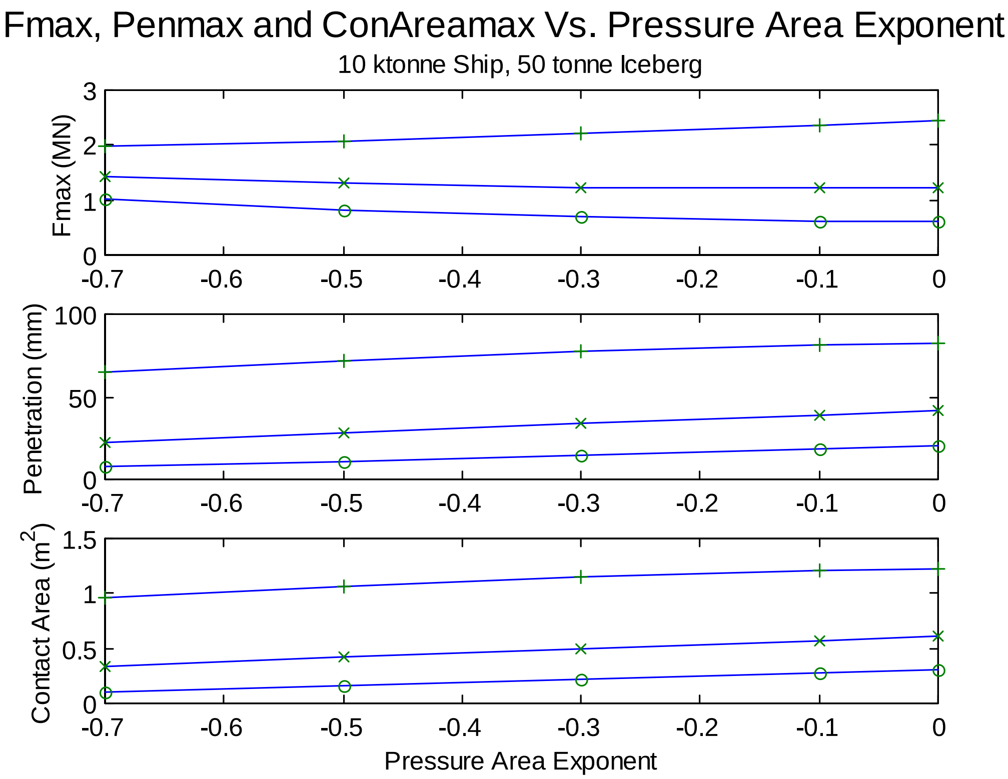

Fmax, Penmax and ConAreamax Vs. Iceberg Velocity
1000 tonne Iceberg with a P-A Exponent of -0.7
Fmax (MN)
Penetration (mm)
Contact Area (m^2)
Pressure Area Exponent

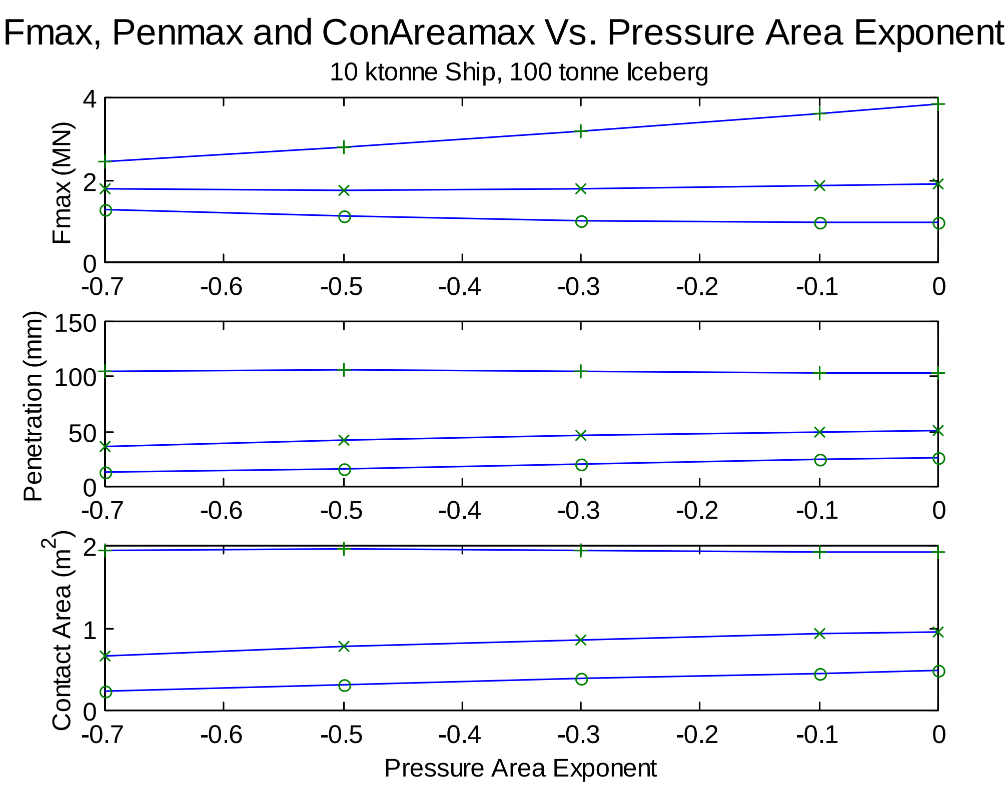
Appendix D:

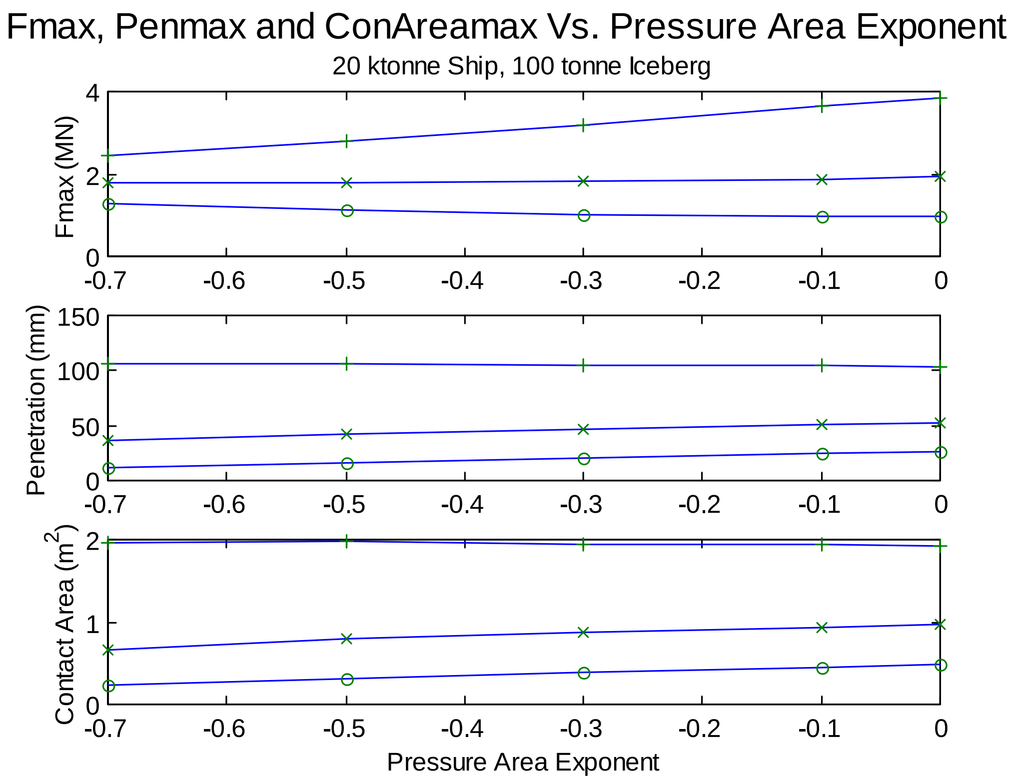
Plots of
Fmax, Penmax and ConAreamax VS. **Area Exponent**
for a family of **ice velocity** curves
(ie. for all combinations of ship and ice displacements)

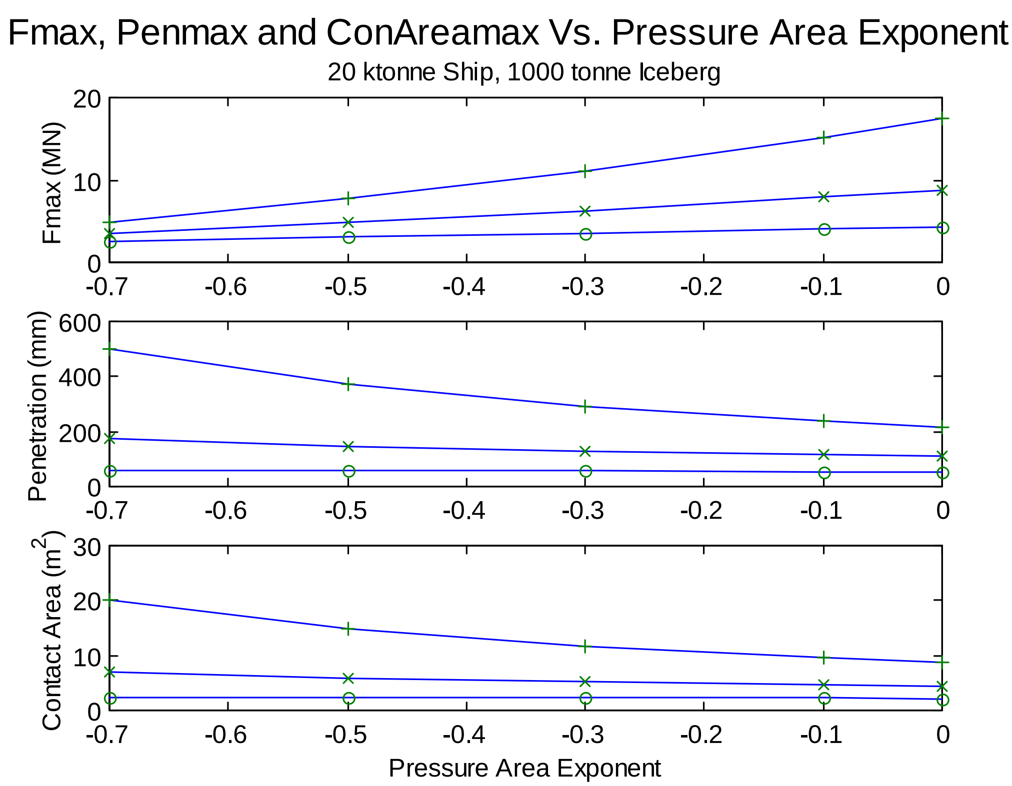
Legend:

Symbol	Ice Velocity (m/s)
O	0.5
X	1.0
+	2.0


Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent
10 ktonne Ship, 50 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent


Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent
10 ktonne Ship, 100 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent


Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent
20 ktonne Ship, 100 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent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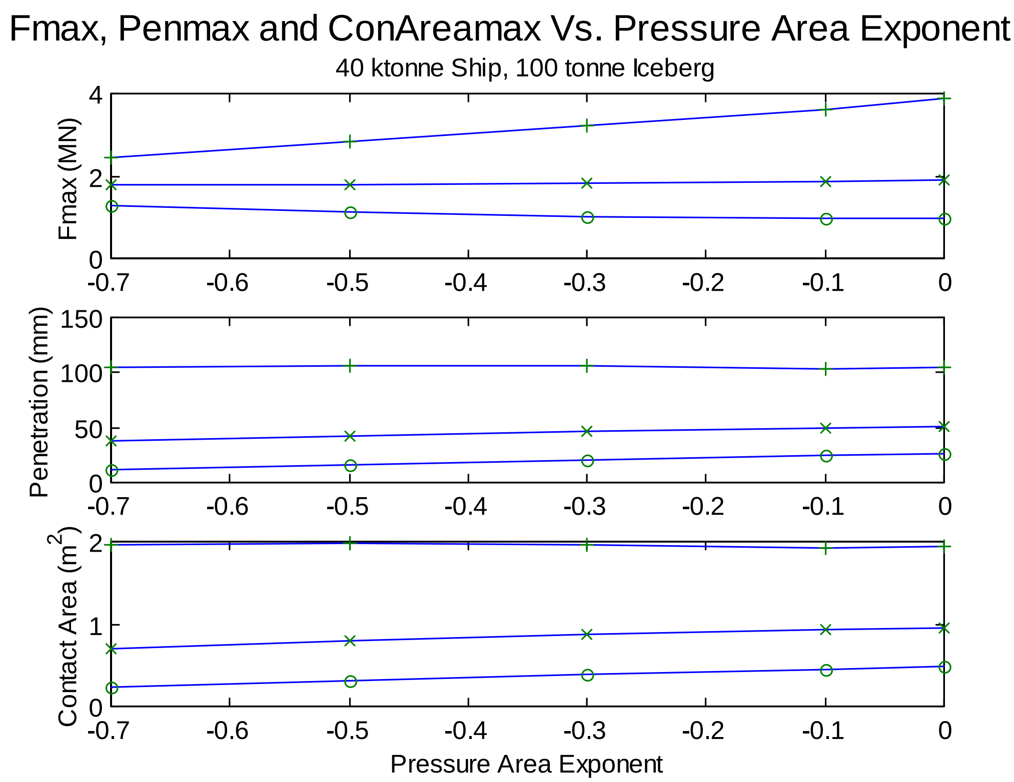
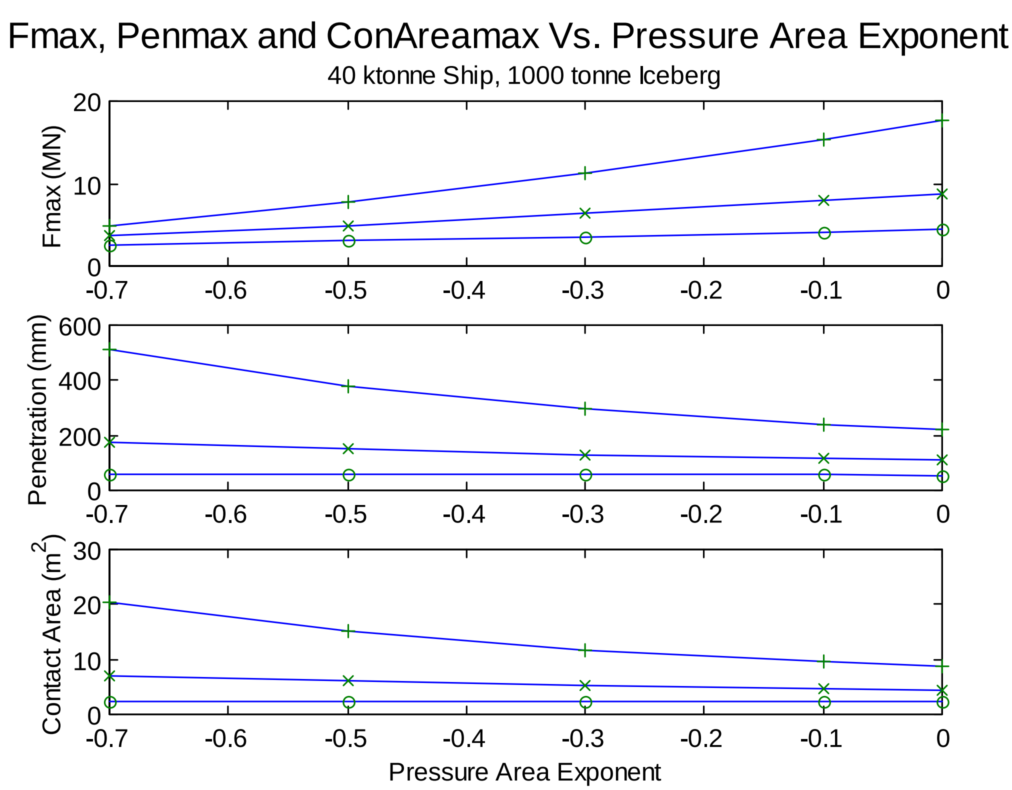
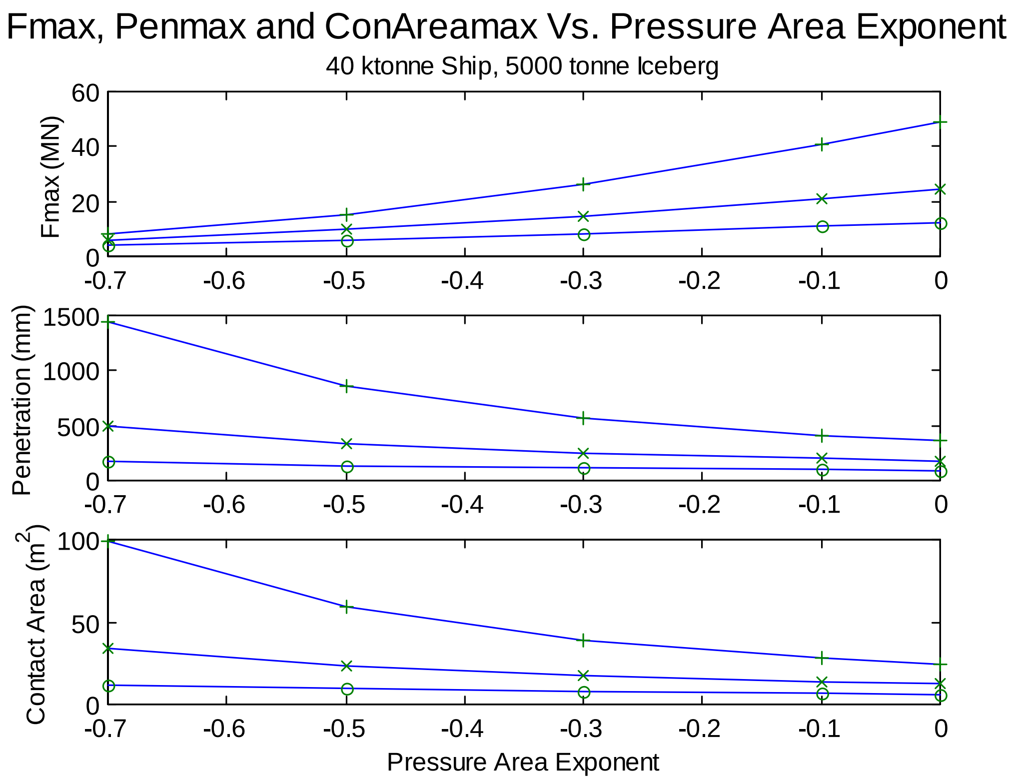
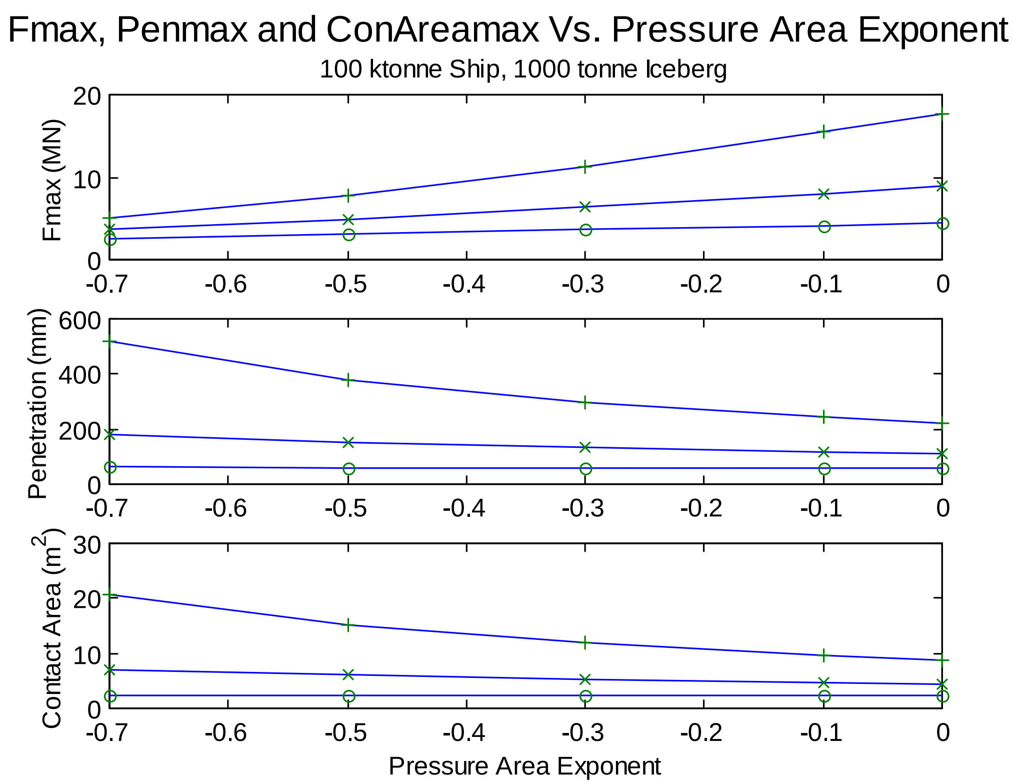
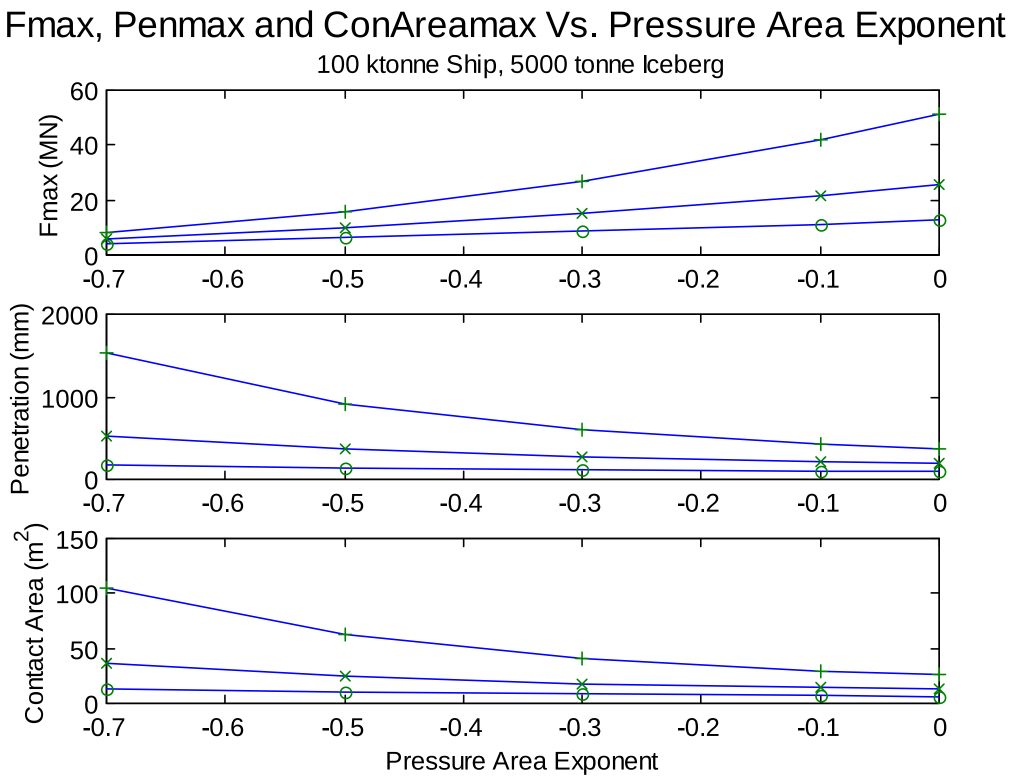
20 ktonne Ship, 1000 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent

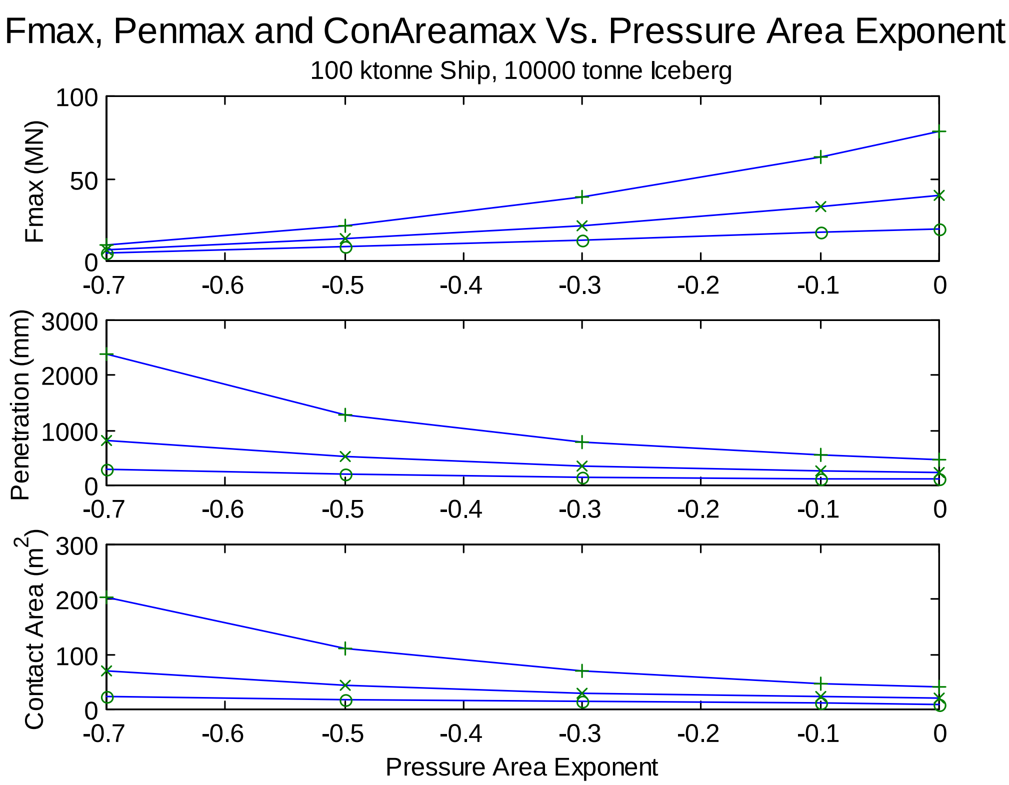

Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent
40 ktonne Ship, 100 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent


Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent
40 ktonne Ship, 1000 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent


Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent
40 ktonne Ship, 5000 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m^2)
Pressure Area Exponent


Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent
100 ktonne Ship, 1000 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m^2)
Pressure Area Exponent


Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent
100 ktonne Ship, 5000 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent


Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent
100 ktonne Ship, 10000 tonne Iceberg
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent

Appendix E:

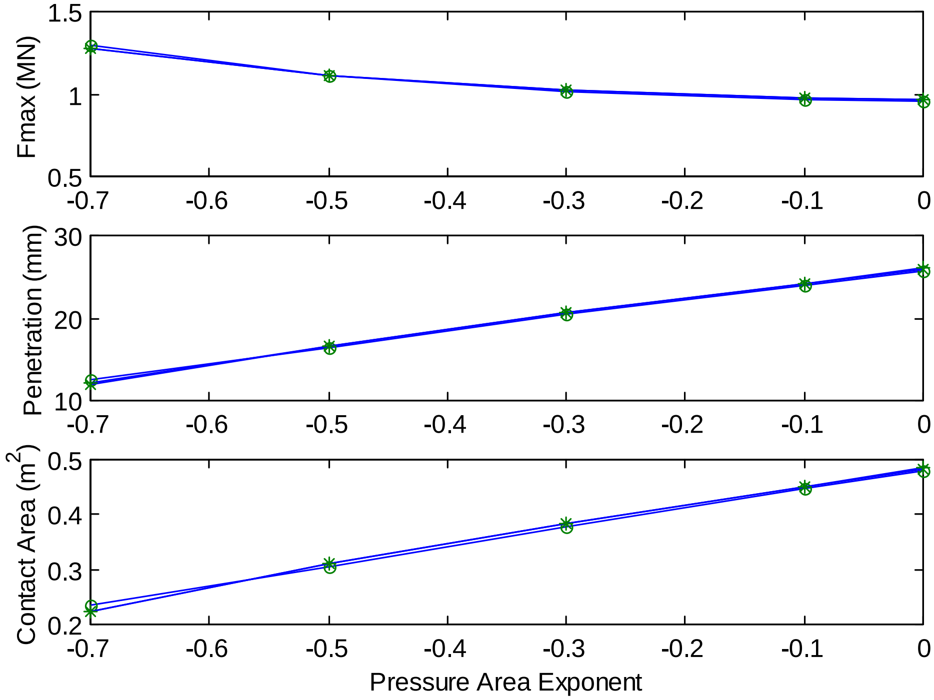
Plots of
Fmax, Penmax and ConAreamax VS. **Area Exponent**
for a family of **ship displacement** curves
(ie. for all combinations of ice displacements and ice velocities)

Legend:

Symbol	Ship Displacement (kt)
O	10
X	20
+	40
*	100

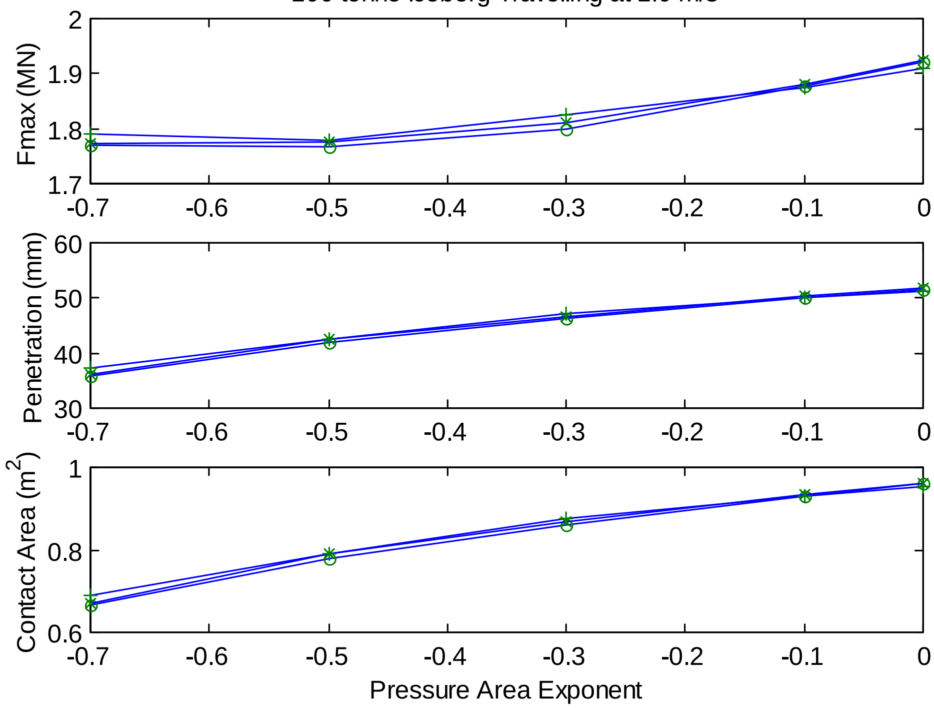
Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent

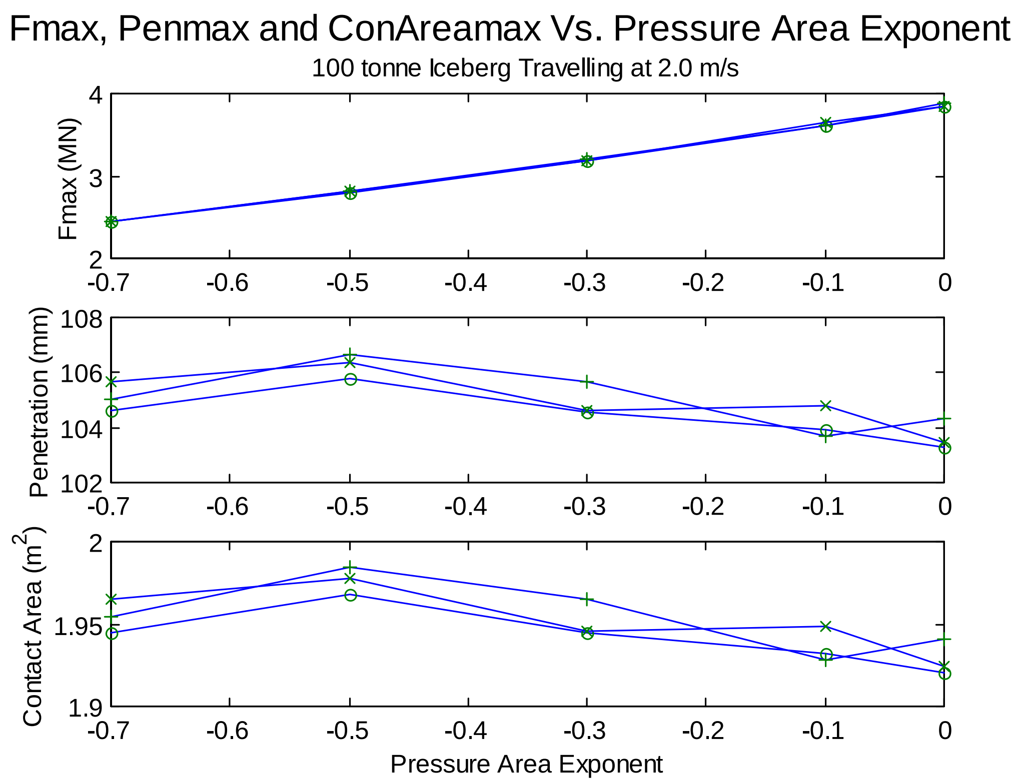
100 tonne Iceberg Travelling at 0.5 m/s

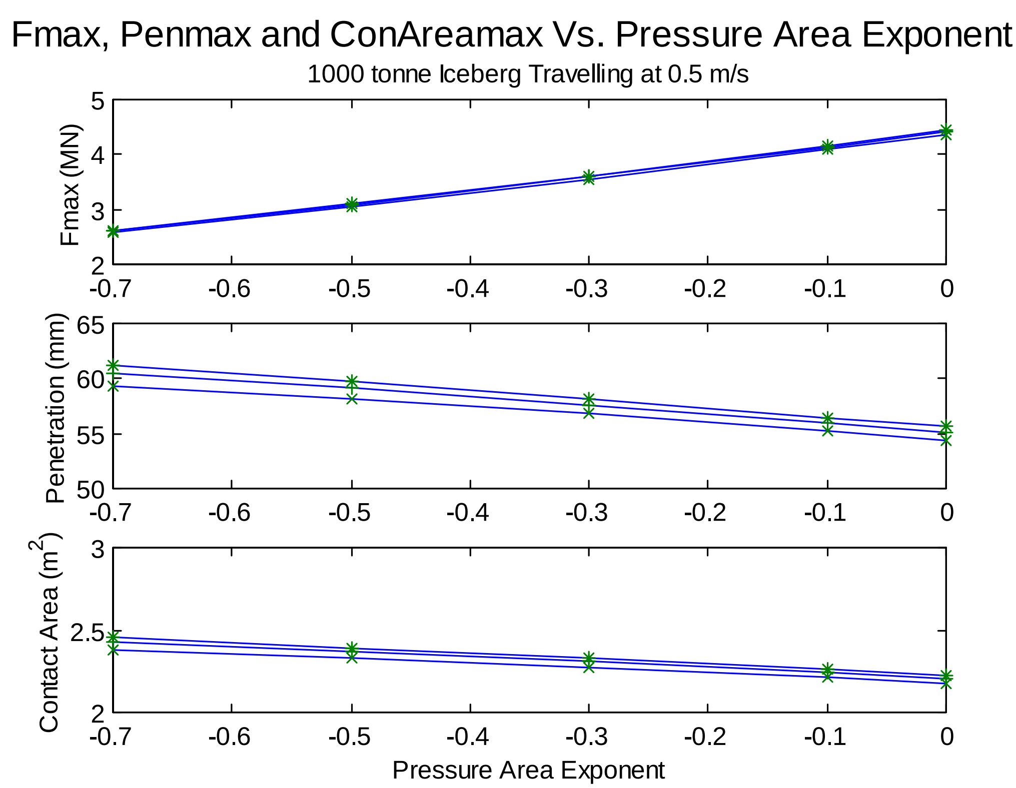


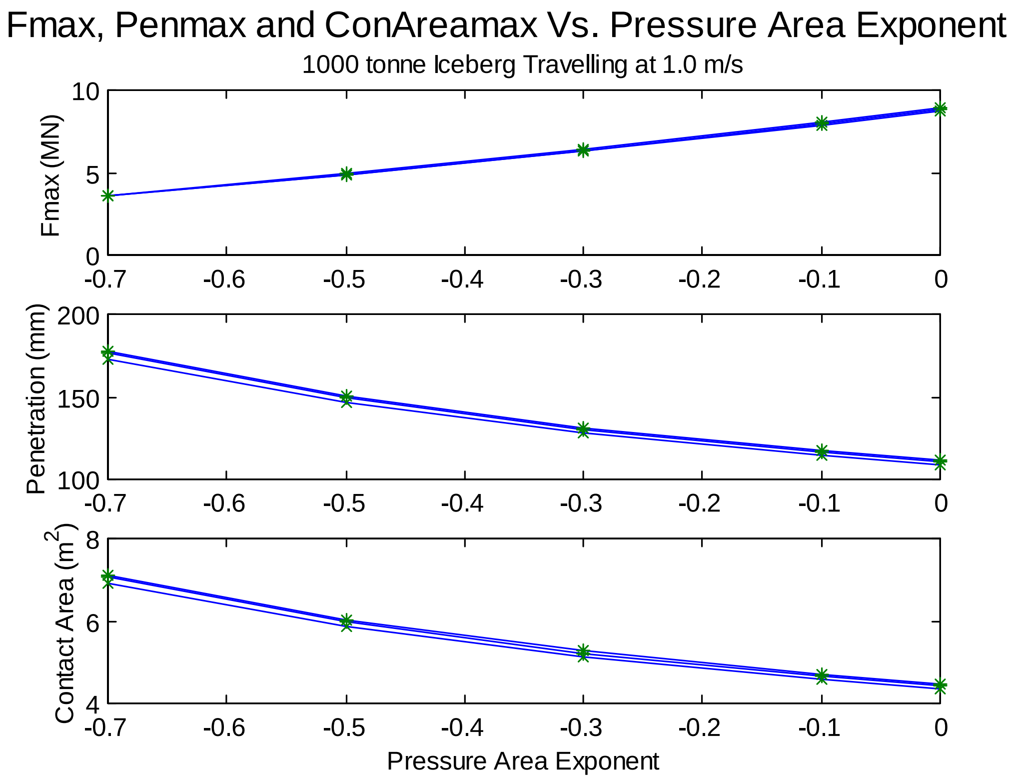
Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent

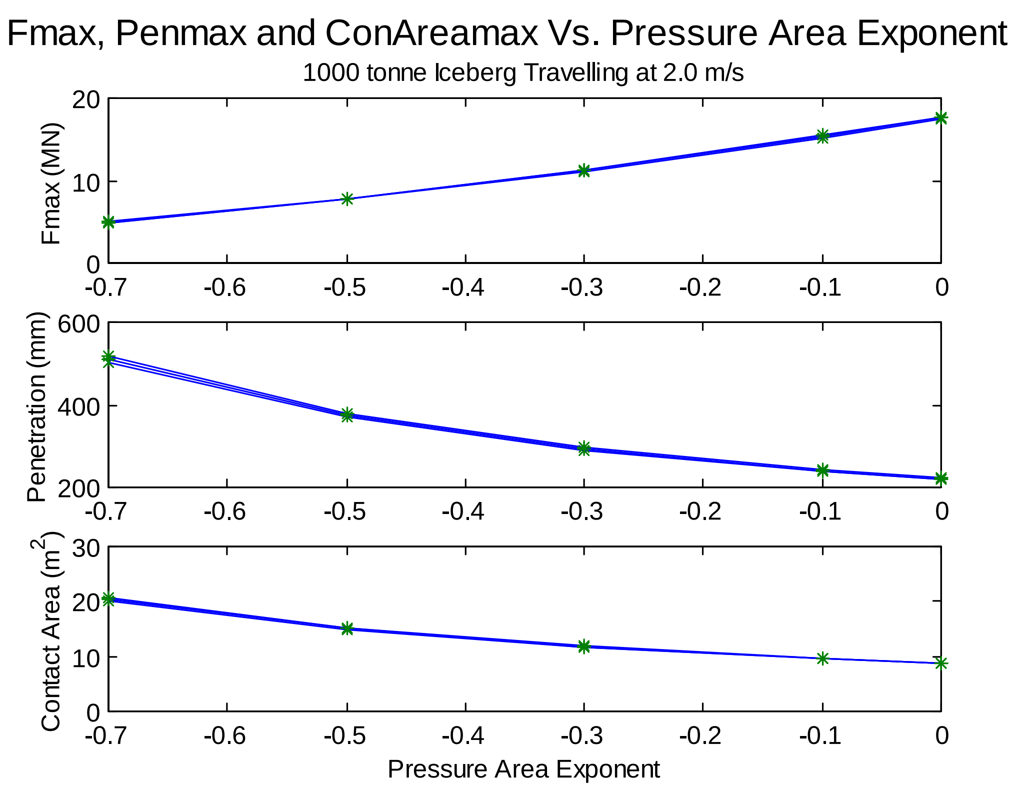
100 tonne Iceberg Travelling at 1.0 m/s




Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent
100 tonne Iceberg Travelling at 2.0 m/s
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent


Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent
1000 tonne Iceberg Travelling at 0.5 m/s
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent


Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent
1000 tonne Iceberg Travelling at 1.0 m/s
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent


Fmax, Penmax and ConAreamax Vs. Pressure Area Exponent
1000 tonne Iceberg Travelling at 2.0 m/s
Fmax (MN)
Penetration (mm)
Contact Area (m2)
Pressure Area Exponent

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<tr><td colspan="2">Abstract

The East Coast of Canada has become one of the major offshore oil regions in the world. The unique aspect of the region is the presence of ice, both in the form of sea ice and icebergs. After a GBS structure at Hibernia, the Terra Nova oilfield is being developed with a ship-shape moored structure. The problem of transverse ship-ice collisions has become a significant concern.

The work described herein deals with the simulation of transverse collisions between a stationary ship and a spherical iceberg moving with constant initial velocity. The study makes many simplifying assumptions, and mainly serves to set the scope of the problem.</td></tr>
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